GEOGRAPHICAL RESEARCH INSTITUTE
HUNGARIAN ACADEMY OF SCIENCES

LOESS inFORM
2

BUDAPEST 1993

QUATERNARY AND LOESS RESEARCH

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Geographical Research Institute
Hungarian Academy of Sciences

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Definition and criteria of loess

The interpretation of the concept of loess — the origin of its characteristic features, the definition of the criteria of loess — has initiated a number of theories, explanations and debates during many decades of loess research. The reason why the loess problem, the differences in definitions, have survived to our days is the different approaches applied by various researchers in various places and at various times to define or describe loess. The most usual loess definitions are based upon its petrographic and genetic aspects.

It is not easy to provide a definition which satisfies all viewpoints since the loess concept is occasionally interpreted rather broadly, while on some geological maps (e.g., in the former Soviet Union) it is interpreted in a much narrower sense. In the literature loess is classed in various ways, some call it rock, others sediment or formation or system. One of the reasons for this is that the subaerial loams, clay loams and other deposits which constitute the mechanical texture of the loess are identified as loess or loess-like formations. Loess is a complicated system formed by biogenous and abiogenous processes. It differs from soils — in the opinion of N.I. KRIGER (1986) — as it shows a much weaker biogenous influence.

The intention to distinguish between loess and loess-like deposits (which are only similar to loess in some of their individual parameters) exists, but the criteria suitable for making the distinction and the available methods for sedimentological analysis have not been applied widely and with equal emphasis.

As comprehensive criteria, the following are usually applied to define typical loess:

1. homogeneous, porous, slightly diagenetized, pale yellow deposit, its material is predominantly coarse silt (10 to 50 microns), which is relatively well sorted and is of 40-50 weight percentage;

2. besides the prevailing quartz grains (40-80 per cent; on the average 60-70 per cent), it contains felspars, calcium, calcite and dolomite in lesser amounts;

3. the individual loess horizons are usually unstratified, but the loess sequence often contains intercalated paleosols or loam or sand beds;

4. the percentage of clay and sand (in weight 5-25 per cent) is of subordinate importance. Among clay minerals the illite or montmorillonite dominates, while in smaller amounts kaolinite, vermiculite and chlorite are also frequently present;

5. carbonate content is variable (ranging from 1 to 20 per cent), depending on environmental conditions; its role is great in cementing mineral grains and in old loess carbonaceous concretions are also characteristic;

6. loess grains are partly cemented and partly aggregated; void ratio is 45-55 per cent — loess is permeable to water;

7. under dry conditions, even steep loess walls are stable, the compression strength of loess is 1.5 kg per dm^2; when saturated with water, easily collapses;

8. easily eroded by surface water-courses; liable to subcutaneous hollow formation;

9. remnants of terrestrial, mostly of cryophile fauna and flora are typical in the loess horizons;

10. the accumulation of the mineral material of loess mostly took place as a result of repeated transport and sorting by air but, due to the impact of rainwater runoff, snowmelt and other processes on the slope, small grains are moved further until they are stabilized by vegetation;

11. the accumulated grains are transformed into loess in some geographical environments (primarily in the zones of cold steppes, warm steppes and forested steppes) through a moderate diagenesis.

Regarding and summarizing the main criteria, true (typical) loess can be described as a loose deposit with coarse silt predominant in grain size, unstratified, porous, permeable, stable in steep walls, easily erodible by the effect of water, „structured light loam" of pale yellow colour due to finely dispersed limonite (iron-hydroxides), quartz as main mineral constituent (40-80 per cent), subordinate felspar content, variable amounts of clay minerals (5-20 per cent), fine sand (5-25 per cent) and carbonates (1-20 per cent).

It is common that among the criteria of typical loess only eolian transport and accumulation are thought decisive, not only as far as the origin of the material is concerned but also for the development of the texture of loess. Another group of loess researchers emphasizes the significance of ecological conditions, bio-geochemical processes related to the vegetation and soil in the origin of the fabric of loess — factors which have already been underlined by RICHTHOFEN.

In addition to the prevailing light mineral fragments, subordinately heavy minerals (rare elements) also occur. Their associations with the clay minerals tell about their source areas, the geographical environment of loess formation.

Distribution of loess

Loess is one of the most extensive formations of the Ice Age. It covers almost 10 per cent of the land surfaces in mantle form. Its distribution is bound by some geographical environments. It is particularly characteristic in semiarid, grass steppe and forest steppe, as well as forest zones of the temperate belt with the exception of land areas covered by ice-sheets during the last glaciation.

The varieties of loess and loess-like sediments developed in close association with the adequate geographical environment; they are able to adjust to the environment by partially changing their properties.

Loess horizons were most typically formed simultaneously with the major glaciation periods of the Pleistocene. Formations older than the Pleistocene glacials and showing the true properties of loess have not yet been identified.

In their largest extension loesses and loess-like deposits occur on plains, plateaus, pediments and major river basins (Loess Plateau of China, Siberian Loess Plateau, Fergana Basin, Russian Plain, Middle and Lower Danubian Basin, Middle Rhine Basin, Lower Seine region, Mississippi Basin and Columbia Plateau in North America and La Plata Basin in South America etc.

Important isolated areas are common in Central Europe, along the middle reaches of the Vistula, Oder, Elbe, Main and their tributaries. Outside the present-day temperate belt, in the Mediterranean zone non-typical loess varieties developed with higher clay content or higher sand content and brownish-pink colour (such as in Kashmir, Pakistan, Iran, Israel, Tunis and New Zealand).

In the loess varieties formed under strong oceanic climatic influence in the temperate belt, the carbonate content is low or none. They are of slightly brown tint and their porosity is much lower than average, while clay contents are higher.

In the cold belt, along the Yukon river of Alaska, loess deposition is observed to continue to our days (PÉWÉ, T. 1968). Considerable actual dust accumulation is recorded on the Loess Plateau of China, in the basins of Central Asia, but soils are being formed today from the dust accumulating in these areas. A special loess variety, the 'yedoma' loess-ice complex, occurs in larger patches in North Siberia, in the permafrost tundra zone (KONISHCHEV, V.N. 1987; TOMIRDIARO, S.V. 1980).

Lithological properties of loess

The lithological properties of loess are largely controlled by the above discussed grain size distribution, mineral and chemical composition as well as the biogenic and abiogenic processes taking place during and after the accumulation of the mineral mass. The characteristic marks of loess are colour, fabric, carbonate content, cementation, aggregation and moisture content.

Colour

1. *Typical (true) loess* is mostly yellow, pale yellow or occasionally greyish yellow. In wet condition its colour on the Munsell scale is 2.5 Y 5/4-6/4-7/4-8/3. When dry its colour is usually lighter because, for example, when dry loess cliff is exposed to long sunshine the carbonates (and also salts) precipitate.

2. *Loess varieties* may be of brownish yellow, brown, brownish-light pink or slightly yellowish pink tint. Locally and in some horizons spots caused by manganese, iron and carbonate concretions and root remnants are visible. The loess or loess loam which have weathered either moderately or strongly are usually of darker colour than the typical loess. The colouring of loess is also influenced by various local factors.

Fabric of the loess adjoining of grains

Typical loess, more precisely the individual loess horizons, are characterized by the lack of stratification. The vertical profile of a loess sequence may comprise loesses of different colour and grain size composition with intercalated buried soils, sand or, locally, layers other than loess. In this sense, the *loess sequence* is subdivided into stratigraphic units or groups, *series,* however, usually there are no sharp boundaries between layers. Erosional hiatuses are seldom visible to the naked eye.

The unstratified nature of loess means that the grains show no discernible orientation in the particular horizons. While in sedimentary rocks grains are arranged clearly in some direction, in a loess series no such regularity can be recognised.

An important property of the loess fabric is the *adhesion of grains* which is due to *cohesion* and *cementation.*

To the *cohesion of grains* surficial energy, hygroscopic water envelope and the surface tension of capillary pressure are contributing factors which are also influenced by grain structure, mineral composition, moisture content and porosity.

The *cementation of grains* is secured by a binding material which primarily is calcareous coating, i.e., calcareous contact cement around the grains and calcareous pore cement filling up the voids. Also, perhaps, there is some iron precipitation.

Porosity

Typical loess is characterized by *high porosity*. Its void ratio may amount to 45-60 per cent. The pores between solid particles are filled by air or water.

The void ratio is largely controlled by carbonate content. Void ratio in carbonate-free loess loam is low (cca 20 per cent). The porosity of young loess is generally higher than that of older loess.

Loesses with high void ratios — particularly in the case of water saturation — are more liable to collapsing and sagging than those of lower porosity.

Loess is susceptible to environmental changes. Its porosity decreases with the increase of precipitation and similarly with artificial irrigation. With reduced porosity, the tendency for collapsing diminishes or ceases.

The *moisture content of the loess* is usually 14-22 per cent and is of ephemeral nature. The amount of water or moisture contained is controlled zonally by environmental conditions. Moisture in loess profiles fluctuates seasonally at 1-3 m depth and at 10-15 m depth there is a 'dead horizon'(KRIGER, N.I. 1984). The change of moisture content within the loess profile is controlled by the variation of grain size and the degree of porosity, particularly on the boundaries of horizons with higher clay contents.

Aggregate content

Resulting from cementation and adhesion of the finest grains the fabric of loess is characterized by the presence of aggregates of mostly 10-50 microns in diameter. Whereas some investigators associate the formation of the aggregates partly with the deposition of grains, others explain it with diagenesis subsequent deposition. Still others doubt the existence of aggregates in the loess, in spite of the fact that particles swell to 10-50 micron size because of $CaCO_3$ hydratation. Moreover, the adhesion of clay minerals in loess also promotes aggregate formation.

Cyclical alternation of loess, sand and buried soils

In the deep loess profiles sand layers are repeatedly intercalated between the loesses and buried soils. L. ÁDÁM, S. MAROSI & J. SZILÁRD (1954) were the first to underline the significance of sand layers in stratigraphy. The debated issue is not only whether the sand is a fluvial, colluvial or eolian deposit, but also whether they are glacial, interglacial or interstadial formations.

The sand layers of different sphericity, transported by various processes, which occur in loess sequence may be eolian, fluvial or derasional (accumulated by transportation processes along slope) sands or redeposited sands.

In the sequences of some loess regions of special locality — particularly in mountain forelands and alluvial fans deposited into a basin — repeated alternations of *loess, sand and paleosols* were observed. In the Danube-Tisza Interfluve, Carpathian Basin, down to 100-140 metres under lowland surface,boreholes revealed about 10 loess horizons subdivided by buried soils and sand layers intercalations. Loess formation is associated with the cold/dry climatic stages, sand accumulation with the drier stages of the interglacials and the weathering and loamification of buried soils and loess horizons with the more humid and warm stages of the interglacials. The 10 cycles of loess horizons correlate with the 10 consecutive glacial stages of the MILANKOVITCH & BACSÁK climatic calendar; the oldest loess horizon, for instance, corresponds to the Günz I glacial (BACSÁK, Gy. 1942; MIHÁLTZ, I. 1953).

On the *loess ridge along the Ob river,* Ya.E. SHAEVICH (1984, 1987) found 11 loess cycles in 100-150 m thick alluvial fan profiles and absolute dating shows a time span of 800,000-900,000 years.

The number and recurrence of the surveyed *loess, paleosol and sand* layers indicate that the verifiable number of cycles can vary in different loess exposures. In general, however, above the Brunhes-Matuyama boundary (0.73 Ma) 8-13 alternations of loess and paleosols — with several sand layers — are observed in the larger exposures (KUKLA, G.J. & LOŽEK, V. 1961).

Syngenetic and postgenetic alterations in loess

a) *One group of scientists* explains the properties of non-typical loesses with *different environmental conditions.* Loess formation primarily occurred during the Pleistocene glacials in several geographical zones. The paleogeographical conditions in these zones varied either considerably or to a limited degree only. The 'superzone' of loess formation (VELICHKO, A.A. 1987; KRIGER, N.I. 1984) included the margins of deserts, grassed steppes, forest steppes, the zones of periglacial grassed tundra and forest tundra;in these environments various syngenetic varieties of loess could develop. In addition, local topography could also have caused major paleogeographic differences.

b) *Another group of researchers* holds the opinion that airborne dust accumulates over extensive regions as a rather uniform, well-sorted material. The differences in loess properties within regions should be explained mostly by *postgenetic alterations*. They assume all alterations to have taken place on the loess surface or in the loess body after the primary eolian deposition.

The so-called *loess derivates*, or secondary loesses, are the ones that, on the one hand, were redeposited along the slopes by various processes and then re-accumulated and became restabilized, on the other hand, the silts which were deposited by rivers and later acquired the properties of the loess. Postgenetic alterations are decalcification, loamification and soil formation on the loess. The resulting materials are often called (epi- or) postgenetic loess varieties.

The fundamental difference between the two explanations for the formation of loess varieties is that one group lays the main emphasis on material accumulation, while the other one on the variations of the geographical environment. The scientists proposing a decisive influence of the geographical environment also envisage postgenetic alterations including reworking.

In each individual case it is not easy to decide whether a given loess variety has been formed through syngenetic or postgenetic alterations. The loesses (loessy or loess-like deposits) which show clear evidence or at least plausible indication that their non-loessic properties have not been formed syngenetically during the process of loessification but at a later date may be called *altered loesses*. This concept, however, is quite often interpreted in different ways leading to many debates and misunderstandings in the genetic classification of loesses and loess-like sediments.

The various syngenetic loess varieties are described in detail at the section on loess classification. Here it is to be noted, however, that the *regional facies of loess, such as brown loess, infusion loess or glacial loam, are not classed with the true altered loesses.*

The loesses which are altered epigenetically in places during the breaks of loess diagenesis are classified into two groups:

1. One group comprises the *sensu stricto altered loesses* — loess loams, grey reductional loess horizons, rusty oxidational loess horizons, decalcified loesses, carbonate concretion zones and the old compact loesses. Their development is associated partly with groundwater flow and the infiltration of rainwater including the impact of their physico-chemical processes and partly with the compaction effect of the overlying layers. In most of the cases no climatic influence can be associated with these alterations.

2. The other group includes *loesses affected by soil formation* subsequent to the diagenesis of the loess. It is to be emphasized that *buried soils cannot always be interpreted as altered loesses*. During the interruptions of loess formation the slow accumulation of dust still continues and — under the changed paleoecological conditions — provides mineral mass for soil formation.

The loamification of loess was mostly induced by temperate oceanic climatic influence and it is common in loess sequences of the mountains.

In the deeper sections of loess profiles, mostly in older loesses, more compacted loesses with higher loam contents occur. Although these loesses have low carbonate content, still they are not entirely free from carbonates. They are of greyish-yellow or brownish-yellow colour. These horizons are subdivided by *carbonate concretion levels*. Below certain paleosols and locally above layers with higher clay content the leached carbonates precipitated as concretion levels or *limestone strata*.

The climatic evaluation of the formation of altered loesses is the most hypothetical aspect of the reconstruction of Pleistocene paleoenvironments.

Paleosols of more frequent occurrence

Most of the soils buried in loess developed during the interruptions of loess formation under different paleogeographic conditions. The alternation of loess and paleosol layers is regarded as an evidence for the cyclic recurrence of Pleistocene climatic changes. The identification of the genetic types of buried soils allow the reconstruction of the paleoenvironments during the periods of their formation and the detection of the trends of Pleistocene climatic changes.

In the loess profiles of Central Eastern and Eastern Europe steppe and forest steppe soils are characteristic. They are also present in younger loesses where now forest soils are the zonal soils. In Western and Central Europe, mostly in the upper sections of the profiles dark humic soils and horizons of weaker humus accumulation are frequent. Old loesses are chiefly characterized by lessivée brown forest soils *(Table 1)*.

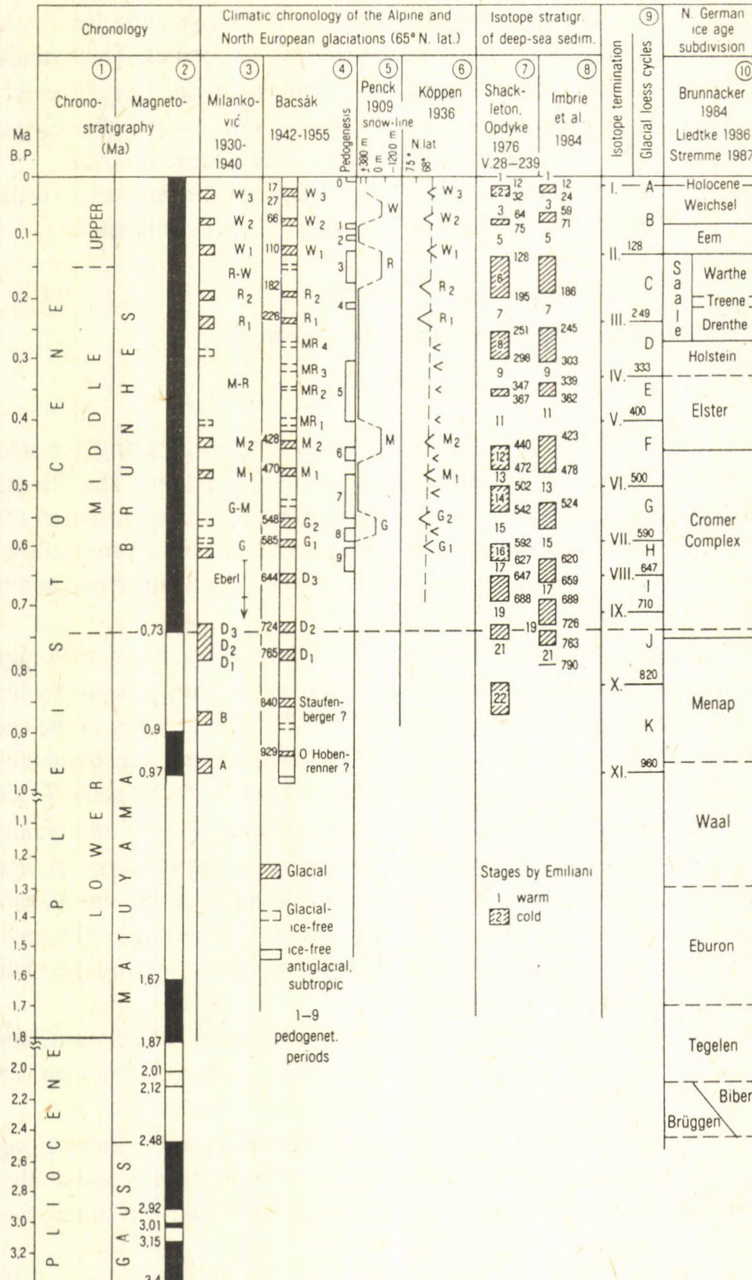
1. *Skeletal soils* and *weak humus accumulations* as *embryonic soils* are repeated in Upper Pleistocene loesses. They are often present as humus-carbonate soils or humic loesses. It seems probable that some humic horizons are remnants of arctic steppe or tundra soils which stopped to develop further at some stage. The time of their formation was rather short. Embryonic soils are not always autochtonous formations, they may also be solifluctional soil sediments.

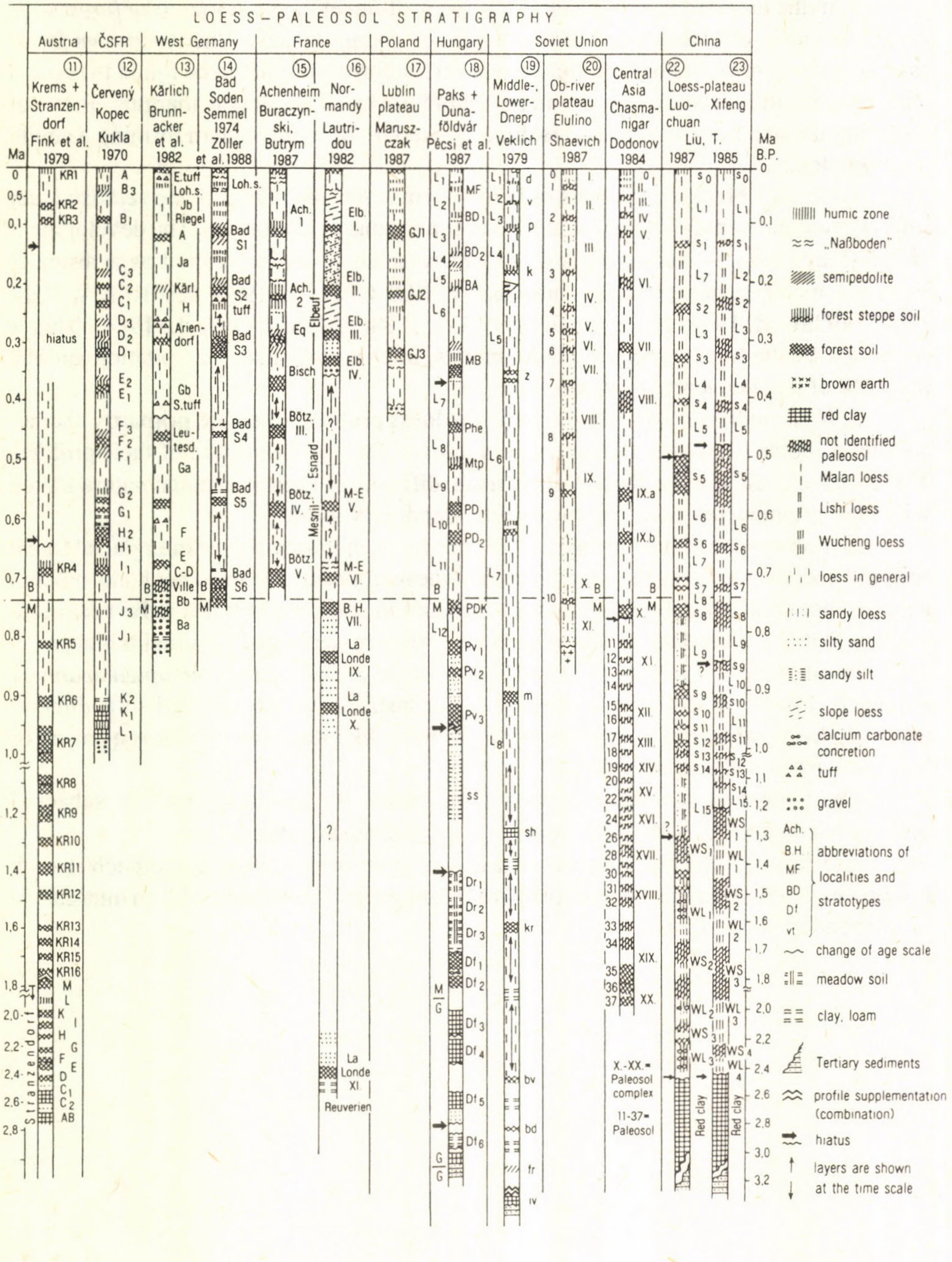
2. *Steppe and forest steppe soils* are typical of the young loess profiles of the Eastern European Plain and the Middle and Lower Danubian Basin where buried chernozem-like soils recur several times.

In the loess profiles of the Black Sea region and in those along the Danube river in Yugoslavia and Bulgaria, the *chernozem-like soils* are occasionally replaced by a *pale chestnut steppe soil*. Both soil types contain carbonates (in some cases gypsum) and are rich in krotovinas.

Chernozem brown forest soils can usually be conceived as the forest steppe facies of the above steppe soils, but there are also indications that forest soils take on chernozem

Table 1. A possible correlation between the Pleistocene glacial chronology, deep-sea oxygen isotope stages




LOESS–PALEOSOL STRATIGRAPHY
Austria
ČSFR
West Germany
France
Poland
Hungary
Soviet Union
China
Krems + Stranzendorf Fink et al. 1979
Červený Kopec Kukla 1970
Kärlich Brunnacker et al. 1982
Bad Soden Semmel 1974 Zöller et al. 1988
Achenheim Buraczynski, Butrym 1987
Normandy Lautridou 1982
Lublin plateau Maruszczak 1987
Paks + Dunaföldvár Pécsi et al. 1987
Middle-, Lower-Dnepr Veklich 1979
Ob-river plateau Elulino Shaevich 1987
Central Asia Chasmanigar Dodonov 1984
Loess-plateau Luochuan Liu, T. 1987
Xifeng 1985
Ma
Ma B.P.
humic zone
„Naßboden"
semipedolite
forest steppe soil
forest soil
brown earth
red clay
not identified paleosol
Malan loess
Lishi loess
Wucheng loess
loess in general
sandy loess
silty sand
sandy silt
slope loess
calcium carbonate concretion
tuff
gravel
abbreviations of localities and stratotypes
change of age scale
meadow soil
clay, loam
Tertiary sediments
profile supplementation (combination)
hiatus
layers are shown at the time scale
X.-XX.= Paleosol complex
11-37= Paleosol

dynamics. Not all dark or black structured soils in the loess profiles can be identified as chernozem. Meadow and meadow-chernozem soils also occur, most commonly in the broad derasional valleys.

3. In the loess profiles of Central Europe well-developed *B horizons of forest soils* usually occur in old loesses and at the bottom of young loesses. Whereas *brown forest soils* occur in continental basins, the lessivée brown forest soils are to be found in regions with oceanic influence and in the more humid zones of mountain margins. It is not uncommon that a brown forest soil is directly overlain by a chernozem forming a single soil complex.

4. Besides brown forest soils or below them *ochre-red clay soil* and *reddish loam soils* (Braunlehme) may also occur in the lower horizons of old loesses. The development of red (clay) soils — during parts of the interglacials — is interpreted as a result of intensive mediterranean climatic influence (BRONGER, A. 1976; KUBIENA, W.L. 1964; PÉCSI, M. 1972, 1985; SIRENKO, N.A. 1984; SMOLIKOVA, L. 1984). This is supported by the high content of clay minerals, intense carbonate precipitation and the presence of large concretions in the soil layer.

5. *Hydromorphic soils* also occur in the loess profiles. They are primarily characteristic in loesses on lower terraces and in alluvial fans at the bottom of their profiles. The climatic evaluation of these soils is made difficult by their intrazonal nature linked with high groundwater table (meadow soils, floodplain soils).

Our observations indicate that, on the one hand, the formation of interglacial forest soils did not cover entirely the whole length of the interglacial. On the other hand, erosion gaps are not at all infrequent in loess profiles and in some cases it has to be taken into account that two soils directly above each other may be separated by a major hiatus.

In our experience, *older loesses almost never provide an uniterrupted sediment sequence*. There are also data to assume — for instance, in the case red soils directly overlying each other and in sequences of old loess-like deposits — that sequences of 'paleosol-erosion hiatus' also exist.

The danger of oversimplification arises when we ignore hiatuses in subaerial profiles which contain more than a dozen of loess-paleosol alternations.

Our long experience suggests that it is also an oversimplified approach if each brown forest soil or steppe-like paleosol in a loess profile is correlated with an interglacial or interstadial *(Figs. 1,2)*.

Paleogeographical reconstruction of the loess, paleosol and sand sequence

Paleosols in loess did *not develop only* under warm and humid or warm and dry climate but occasionally under cold and humid conditions. Similarly, loess horizons are not merely products of one kind of cold periglacial climate. Depending on the type of loess various paleoenvironments can be reconstructed.

The *identification of the genetic types of paleosols*, cryophile and cryophobe phenomena allow the reconstruction of the paleoenvironments of their formation period and the detection of the trends of Pleistocene climatic changes. In Central Europe only fossil brown forest soils are believed to be interglacial forms, whereas steppe-like and humus-rich embryonic paleosols are assumed to have formed during interstadials or during the more humid substages of glacial periods.

This interpretation cannot even be applied within Europe because fewer paleosols occur in the young loess in the immediate vicinity of the continental ice sheet than in those parts of the periglacial zone lying at a greater distance. Similarly, loess profiles in some more humid regions or in watershed positions are less minutely subdivided by paleosols than those in some more arid areas and in subsiding basins.

The paleoecological significance of sand horizons, periglacial phenomena, gaps and buried dells intercalated in the loess-paleosol sequence is also open to interpretation. If the sand horizon is of wind-blown origin, it was most probably deposited during a (peri)glacial period, whereas those who claim it to be fluvial sand, would give it an interglacial origin. Horizons of fluvial sand in the loess mostly represent unconformities. In our experience, the older loess almost never provide an uninterrupted sequence.

In the subaerial sequence developed before the Jaramillo event paleosols predominate, which are mostly pink and reddish, red-brownish clayey-silty soils and the underlying red clays referring to subtropical semihumid climate of seasonal rainfall.

Usually, the paleosols overlie each other. It can be stated that the paleoecological conditions were generally unfavourable to help the accumulated mineral substance transform into loess.

Origin and classification of loess

A most common way of *classification* is *by grain size* when typical (true) loess and loess-like deposits (sandy loess, loess loam, clayey loess and loess derivates) are identified. In the practice of engineering in soil mechanics, additional parameters (such as porosity, compressive strength and others) are also applied. In such investigations and classifications the main aspect is not the origin of the loess, but the assessment of its petrographic and mechanical properties (e.g., susceptibility to collapsing).

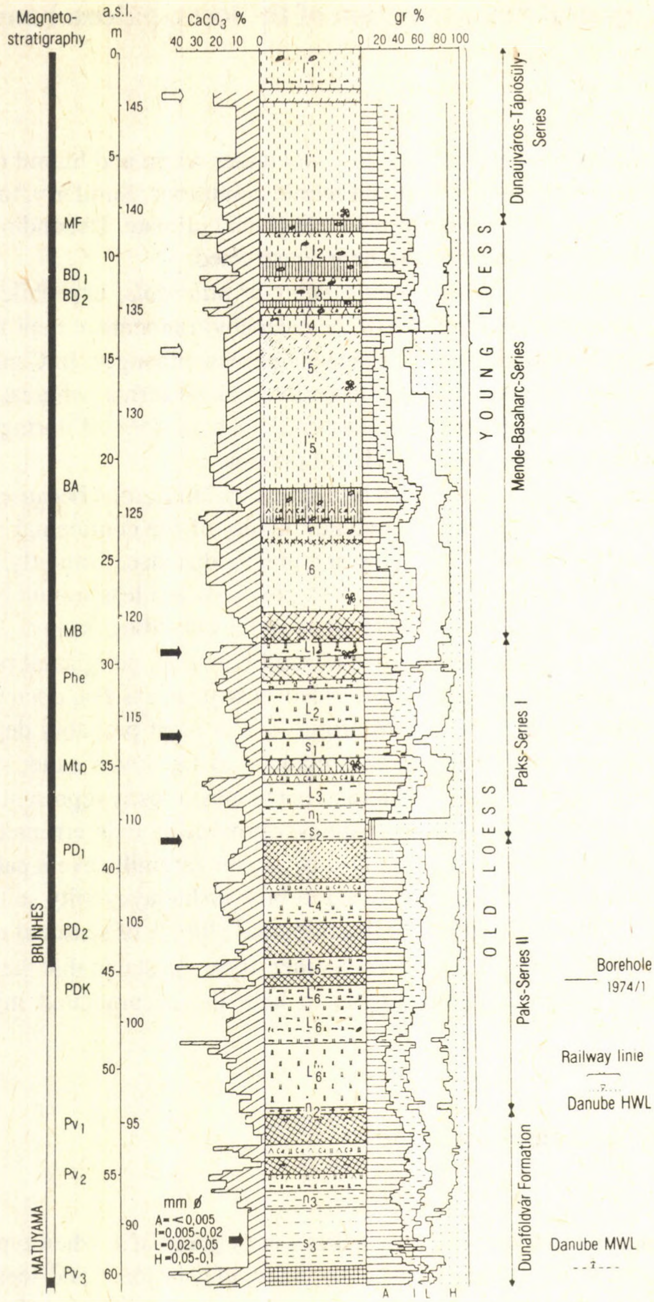


Fig. 1. Lithostratigraphic subdivision of the loess formation at Paks in Hungary. Lithological and pedological analysis made by M. PÉCSI, E. SZEBÉNYI, paleomagnetic measurements by M.A. PEVZNER (Institute of Geology, Acad. of Sci. USSR, 1974).

From the geological, stratigraphical, geomorphological and pedological viewpoints loess and loess-like deposits are often *classified by their origin*. This classification is usually combined with the parameters resulted from the analyses of grain size distribution and mineral composition. Recently, soil micromorphological and electron-microscopic analyses of grain shape and structure are spreading.

An important condition for the classification by origin is a sufficient knowledge about the circumstances of loess formation which have been debated in the details for more than a century. In the process of loess formation four groups of factors are predominant: conditions and locations of the formation of *grain shape* (1), *material transport* (2), *accumulation* of particles (3) and finally in situ weathering, i.e., the *diagenetic* processes (4). Even today there is a considerable disagreement about which one of the four groups of factors is the most definitive with respect to the formation and the classification of the numerous varieties of the loess.

The coarse dust fraction can be derived from mechanical weathering caused by frost action or insolation, from comminution caused by glacial ice, originated from till and outwash material and, finally, from fine textured fluvial and lacustrine deposits, or often from sandy deserts.

There are two major groups of explanations for the accumulation of the mineral material of loess. The first one is simpler, rather text-book like (a), while the other one is rather complicated and assumes multiple reworking (b).

a) The predominant grain size composition, transport and characteristic sorting of typical loess is explained in the simplest way by wind action. The arrangement of grains without orientation in the loess is also accounted for by the accumulation of dust settling from the atmosphere. The material accumulated from such an eolian transport is called 'primary loess' and it is also considered typical loess. If accumulation takes place due to

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Fig. 1.

l'_1, l''_1 = the typical youngest loess beds of the profile; between l'_1, l''_1 sandy slope loess deposited in a derasional valley (dell) the lower part of $l''_1(x)$ fragments of reindeer bones as well as locally 1 to 2 humus horizons occur; MF = chernozem-like paleosol of "Mende Upper" only the MF_1 remained; l_2, l_3 and l_4 = young loess beds below paleosols (MF_1, BD_1 and BD_2) with numerous krotovinas in it; BD_1 and BD_2 = "Basaharc Double" paleosol complex, chernozem-like, locally hydromorphous meadow soil type; l'_5 = well-stratified sandy slope loess, the loessic sand filled up the derasional valley (with *Cervus sp.* and *Elephas primigenius* fauna remnants); l''_5 = sandy loess; BA = "Basaharc Lower" chernozem-like forest-steppe paleosol; l_6 = the lowermost young loess bed (with *E. primigenius* remnants) with a thin layer of volcanic tuffite on the top; MB = "Mende Base" paleosol complex; the upper part is forest steppe soil, and the lower one is a well-developed brown forest soil; L_1 = old loess, sandy loess, with large'loess dolls'; molars, tusks of *Elephas trogontherii* were found at two sites; Phe = weakly developed sandy brown forest soil; L_2, L_3 = old loess (with 2-3 layers of 'loess dolls'); Mtp = hydromorphous paleosol (flood-plain clayey soil) with *Allohippus sp.* teeth.; s_1, s_2, n_1 = sand and sandy, silty clay of alluvial fan; PD_1, PD_2 = stratotype of "Paks Lower Double" paleosol complex with krotovinas (sub-Mediterranean xerophile forest soil or chestnut, usually reddish-brown soil) between the PD_2 and PDK paleosols the Brunhes-Matuyama boundary is observed; L_4, L_5, L'_6, L''_6 = old loess horizons with 'loess dolls' layers; L'''_6 = lowermost old loess horizon with rare 'loess dolls'; n_2, n_3 and s_3 = sandy, silty clay and sand of alluvial fan; Pv_1, Pv_2, Pv_3 = reddish, ochre-red paleosols below the old loess. This profile corresponds to the northern side of the brickyard

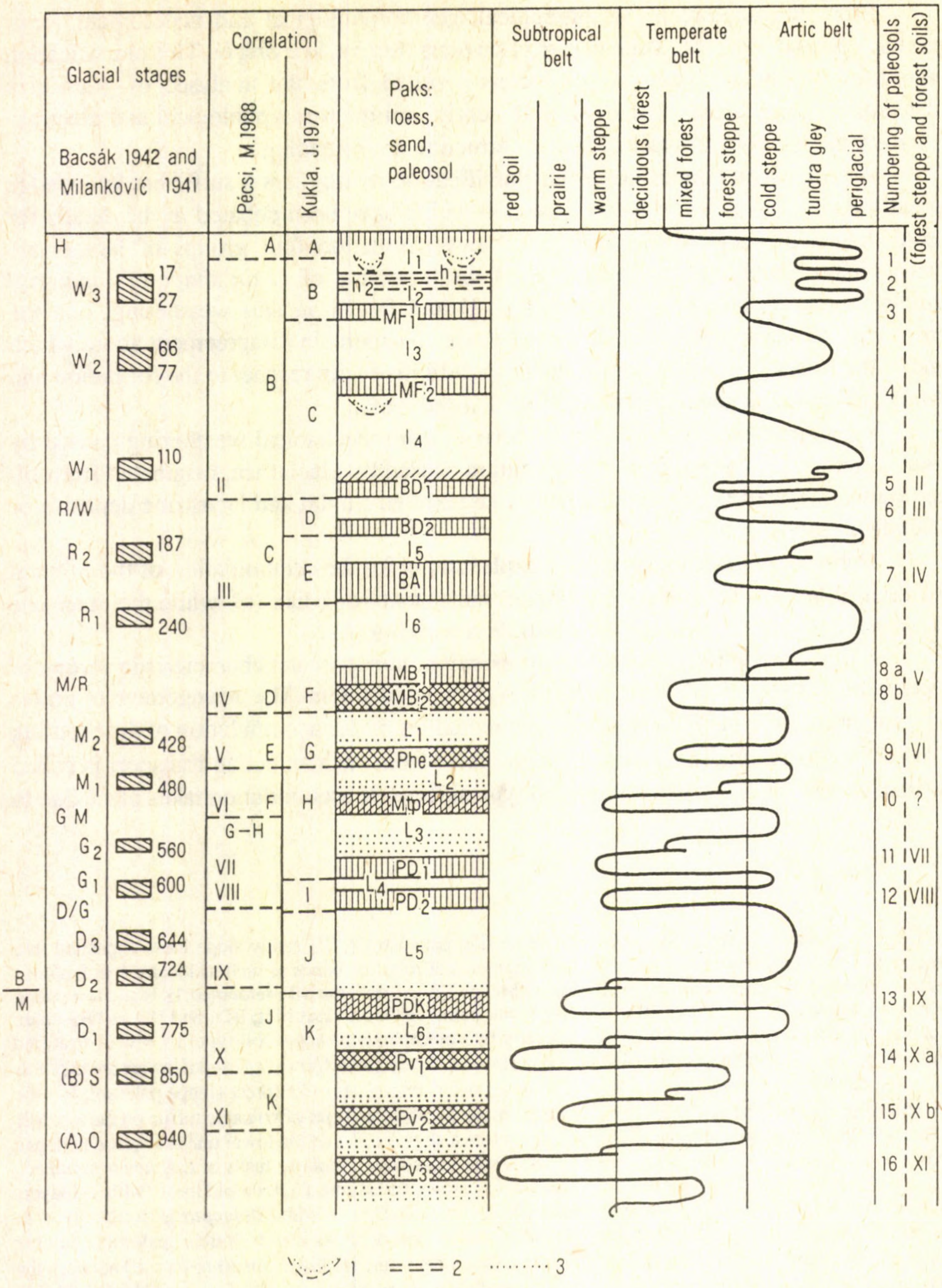


Fig. 2. Cyclic change of loess, paleosol and sand in the loess profile at Paks, Hungary
1 = dells with sandy loess; 2 = embryonic paleosols; 3 = sand layers

other exogenous processes (sheet-wash, solifluction or fluvial action) or these processes cause redeposition and repeated deposition, the resulting material is called 'secondary loess' and mostly not included among typical loesses.

b) According to another group of explanations in the transport, sorting and *accumulation of loess and particularly of its varieties several other agents also took part.* The origin and mineral composition of loess grains and the percentage of heavy minerals indicate a not-too-distant source region for the silt (that is, the *non-exotic* origin of the loess) which was deposited *through double or multiple transport* from major catchment areas (RICHTHOFEN, F. 1882; SMALLEY, I.J. 1980).

For long there have been explanations of loess origin which regarded the *geographical environment a dominant condition* and emphasized its organic and inorganic processes over any group of transport and deposition factors (KRIGER, N.I. 1965, 1986; PÉCSI, M. 1974, 1987b).

Major theories of loess formation

Most of the almost hundred theories of loess origin are concerned with the transport, sorting and accumulation of the base material of loess. A smaller part of them deals with the complicated environmental-geochemical processes of loess formation. The heterogeneity of views is partly attributable to the differences in the properties of the studied loess regions and of loessic formations and partly to the variations in the methods, approaches and other circumstances of research.

1. In the first half of last century loess formation was held to be a flood-plain deposit from fluvial action. This theory was elaborated and supported by Ch. LYELL (1834) himself. Other explanations of loess, such as marine or lacustrine deposit, also occurred.

2. It was the French VIRLET d'AOUST (1857) who *first* advocated the *eolian origin of loess.* At that time, relying on his experience in Europe, even RICHTHOFEN regarded loess a fluvial deposit and only changed his view on the origin of loess after his journey to China. However, along with the action of wind in the accumulation of loess material, RICHTHOFEN always mentioned the role of wash from runoff and rainfall in his later works.

OBRUCHEV identified two types: *'warm'* and *'cold' loess* (OBRUCHEV, V.A. 1895, 1945). In the zone of 'warm' loess he assumes dust transported by winds from deserts and accumulated in wind shadow. The mineral material of 'cold loess' was also transported by winds from the marginal areas of one-time ice-sheets, out of till and fluvioglacial deposits, to their present locations. There are both supporters and critics of this theory of cold periglacial and warm desert-margin loesses established by OBRUCHEV.

There is a long history of attempts to combine the fluvial theory with the eolian one. According to B. WILLIS (1907), the loess deposits of the Chinese Plain were accumulated by the Huanghe as fluviatile silt during the summer period and they were reworked by wind in autumn and spring.

3. As early as the middle of the last century some held the opinion that *sheet-wash* played a predominant role in the accumulation of the mineral material of loess. After RICHTHOFEN this view was propagated most intensively by the Russian A.P. PAVLOV (1889). His theory is grouped with the *deluvial explanations of loess origin.*

Over the slopes of hill and mountain regions the fine material deposited by wind was redeposited — in the opinion of several researchers — by solifluction, wash by meltwater and rainwater (or their joint effect — as covered under the collective name of derasion by PÉCSI, M. 1964, 1968). These kinds of loesses, mostly rhythmically stratified parallel to the slope, are considered to be of *eolian-nival or eolian-fluvionival origin.* Such loesses of filling dells or minor valleys, are sometimes called 'valley loess' (LÓCZY, L. sen. 1886, 1913). Collectively, these deluvial-colluvial loess types appear as *derasional loess* on the loess map of Europe (FINK, J. *et al.* 1977).

4. The theory about the *glacial-fluvioglacial origin of* loess also dates back to last century (LEVERETT, F. 1886; TUTKOVSKI, P.A. 1899). In this theory the fine debris comminuted by glaciers or ice-sheets was accumulated by fluvioglacial waters. Complementing this theory with the eolian and fluvial explanations of loess origin, some (SMALLEY, I.J. & VITA-FINZI, C. 1968) attempted to establish a complex explanation (see later too).

5. *Loess is a product of soil formation.*

L.S. BERG's (1916) theory is based on the fact that in most of the cases the traces of soil formation are recognizable in the loess, locally or by horizons, occasionally rather poorly, but elsewhere — as in the case of paleosols — more strikingly. He regards loess a periglacial dry steppe soil or a warm semiarid steppe soil respectively.

6. Several kinds of processes can accumulate the initial material of loess formation. According to M. PÉCSI, (1967, 1974), various — eolian, derasional, fluvial, fluvioglacial, eluvial and pedogenetic — processes, alternating in time and space, accumulated this material. In the process of loess formation zonal and partly local environmental factors and pedogenetic-geochemical processes were decisive.

7. Recently, the so-called *environmentalistic concept of loess formation* has been put forward. Its proponents emphasize *the role of the physical environment* instead of the circumstances of sediment accumulation. According to them, the properties of loess depend on the present-day and Pleistocene geographical environments (KRIGER, N.I. 1965, 1986; LOŽEK, V. 1968; PÉCSI, M. 1968, 1987a,b).

As an oversimplification, it is often stated in literature that the eolian theory of loess formation is hardly questioned by anyone nowadays. In reality, however, many major loess profiles appear to indicate that the mineral material was accumulated by different processes and it was affected by cyclically different paleogeographic influences. This has already been pointed out by many, including RICHTHOFEN.

Richthofen's model of loess formation

RICHTHOFEN's theory of loess origin does not only count with mere dust accumulation as it can be frequently read. Neither is it a simple confirmation of VIRLET d'AOUST's eolian theory, expressed in 1857, but is richer and more complex than that. RICHTHOFEN clearly described that, whereas dustfall does or may occur in any regions of the Earth, the dust is not converted everywhere into loess.

In fact, RICHTHOFEN identified three main agents responsible for loess formation: accumulating dust; sheet-wash by rainwater under steppe conditions and the soil-forming effect of steppe vegetation.

From the combined effects of these three factors some created the theory of eolian dust accumulation, others emphasized material accumulation by runoff, deluvial-colluvial processes, while still others pinpointed the exclusive role of eluvial soil formation. It can be stated RICHTHOFEN's complex approach to loess formation gave impetus to the elaboration of three other frequently applied theories based on eolian, deluvial-colluvial and soil forming processes.

The impact of RICHTHOFEN's complex concept on loess origin is demonstrated by the recent attempts which assume repeated redeposition of material (SMALLEY, I.J. & VITA-FINZI, C. 1968).

According to RICHTHOFEN's subaerial theory, the true loess was formed in two different climatic stages: first a continental dry climate was characteristic when material accumulated, in the second stage, however, precipitation increased and erosion dissected the surface into interfluvial regions leading to loess formation in the basins covered with steppe. Today it seems to be an overstatement to separate the above two stages in time and space so strictly although dry and wet spells undoubtedly alternated during loess formation. It should also be mentioned here that RICHTHOFEN neglected the alterations of loesses and paleosols within a single loess profile.

Attempts to explain the origin and the conditions of accumulation of quartz grains in loess

A recurring problem of the theories of loess formation is the origin of *quartz grains* of 10-50 micron size which make up the majority of loess material. Therefore, the fundamental question is how the huge amounts of quartz grains of silt size are produced.

Many hold the view that coarse silt is the final product of cryofracture and make efforts to find experimental evidence for it. They hold frost action under cold glacial climates responsible for the creation of silt in amounts large enough for loess formation.

Others emphasize that it was the glacial ice that comminuted rock detritus to grain size mentioned above and it was accumulated by meltwater in fluvioglacial deposits.

Finally, quite a few scientists have the opinion that quartz grains of proper size can also be found in sufficient amounts in river load. Rivers transport loess fraction partly from the detritus comminuted in high mountain zones and deposit it over the flood-plain during floods. Some connect this process with the transport and accumulation of fluvio-glacial material.

The supporters of the soil formation theory explain the development of the grain size composition of the loess partly by mechanical weathering by frost action and partly by biochemical disintegration, i.e., by in situ processes. According to them, coarser grains are partly comminuted by frost and soil formation processes and partly clay particles coagulate, aggregate into grains falling into the loess fraction.

According to SMALLEY, in the first place glacial grinding produced quartz grains, which were further transported by eolian processes, deposited somewhere, but eventually spread over the surface predominantly by rivers.

Most of the Chinese loess researchers trace the origin of the loessic sediments of the Loess Plateau of China to the dust from the Inner Asian desert.

The concept that anticyclonal winds and rivers joined to transport the loess material to the desert and on to the zones of desert margin and deposited it there is, in fact, one of the possible combinations of glacial and desert, ie. 'cold' and 'warm' loess theories.

SMALLEY & KRINSLEY (1978) denied that the example of loess origin in Israel provides sufficient evidence to derive the majority of silt size particles from desert dust. In their opinion, the amount of coarse quartz silt produced in sand deserts is insufficient to provide the source material of loess. Citing the example of the Tashkent loess, they emphasize that its quartz grains material eventually derives from the desert, but a large portion of particles came about during frost and glacial action and were transported to the deserts from high-mountain environments. Consequently, desert is only an intermediary stop in transport, but not the primary source of silt fraction. This concept was first set up by RICHTHOFEN.

SMALLEY (1980, 1986) assumed 9-10 stages to follow the route of silt to its depositional site. Major redeposition is carried out by rivers and wind through two- or multifold reworking.

Loess is not just the accumulation of dust

Loess is not simply dust carried and deposited by wind. Dust only becomes loess after the passage of a certain amount of time in a given geographical zone, i.e., only through diagenesis in certain ecological environments. To state that loess is of eolian origin is an oversimplification and an incorrect definition because an eolian origin applies only to the dust from which the loess has been formed.

We are aware of the fact that airborne dust cannot be transformed into loess in every geographical environment, but only under those conditions typical of semi-arid grassland or steppe or forested steppe. The process primarily occurs where the rate of dust accumulation exceeds sheet wash or weathering (soil formation) rates. If the rate of dust accumulation is less than that of surface erosion or of soil (biogenic) processes, the dust then develops into soil or, through intensive weathering and increased precipitation, into loam or clay.

Only part of the eolian dust transported and deposited in a zone suitable for loess formation remains there permanently and is transformed *in situ* into loess. Dust not affected by diagenesis is usually further transported by snowmelt or rainwash and is only transformed into loess after it has been redeposited. The loess itself, however, is easily erodible and its minerals are readily reworked and reaccumulated and, given the appropriate conditions, it readily undergoes diagenesis again.

We do not always have sufficient evidence to determine whether a given loess body is of primary or secondary origin. Traditionally, the mineral making up 'primary loess' have been regarded as originating in dust accumulated by eolian processes. 'Secondary loess' by contrast is different from typical loess in many ways and it is not unusual to find various loess series in which superimposed dust fractions have been transformed into loess by different processes.

Recently we have observed that the origin of various types of loess is governed by differences in (litho)ecological conditions rather than by the way in the mineral material from which the loess is derived (dust) has been primarily accumulated. Loessification is therefore determined by environmental conditions.

Classification of loess and loess-like deposits on the loess map of Europe

As early as in the mid-sixties, the Commission on Loess of the International Union for Quaternary Research set the objective of surveying the loess types in Europe and representing them on a map of 1 to 2.5 million scale.

No uniform concept has ever been formed among European researchers on the classification of loess types and several names have been in use for formations of basically identical character.

Finally, the Commission on Loess inclined to accept the definition of loess as a formation of primarily eolian origin. In addition to loess as a main category, the other formations were grouped lithofacially as loess-like sediments.

The loess (i.e., the typical and/or primary-eolian loess) as the main category of mapping has also resulted from a compromise. In many thick loess mantles, particularly over hills and valley slopes, in addition to the younger and older loesses, there are varying amounts of sand and sandy or loamy loesses part of which are stratified, so-called secondary loesses, that were also transported along the slope. At certain places half of the strata in the exposures demonstrate such a lithological situation.

Under different relief and climatic conditions the loesses show different varieties which may have resulted from the considerable transformations over the period since its formation. In order to describe and classify these varieties, some members of the editorial board of the map (HAASE, RUSKE, LIEBEROTH and H. RICHTER) suggested the collective term of 'loess derivate' and the proposal was approved by the Board.

Eventually, the Board decided on distinguishing 14 mapping categories on the map of loess and loess-like deposits in Europe and, as supplementary categories, blown sand and cover sand were also included. Thus, the total number of the categories for mapping amounted to sixteen which are summarized below.

The typical loess itself was mapped according to the following three categories:

(1) loess 5 m thickness, and above,

(2) loess below 5 m thickness and

(3) loess in discontinuous distribution.

For grain size composition the coarse silt (20-60 microns or 10-50 microns, respectively) is predominant. The typical loess is usually unstratified, calcareous, has a capillary structure and when dry, its colour is yellow or brownish yellow (10 YR 6-7/3-4 and partly 2.5). Synonymous denominations are typical loess, eolian loess and primary loess.

(4) *Derasional loess* has a grain size composition similar to that of the typical loess (20-60 or 10-50 microns) and this coarse silt fraction makes up about 50 per cent of its total volume. As a result of solifluction and slope wash, this loess type shows a weak stratification. It is also calcareous, porous with capillary structure and its colour is yellow or yellowish brown (10 YR 6-7/3-4). Synonyms are slope loess, finely stratified loess, valley loess, etc.

This loess type was studied in most detail in Hungary, in the loesses of the Transdanubian Hills. This loess was redeposited by weak slope wash, solifluction and other slow mass movements along the slope. For these processes PÉCSI (1966, 1967a) suggested the collective term of *derasion*. On some sloping surfaces or in derasional valleys (dells) this type of loess can be mapped as an independent formation.

(5) *Clayey loess*:

In its grain size composition the fraction of 20-60 or 10-50 microns is prevalent, but it also contains 25-30 weight per cent of clay; mostly unstratified, medium porous, calcareous and capillary in structure; its colour resembles to loess or perhaps somewhat darker.

(6) *Sandy loess*:

In its grain size distribution 40-50 per cent is made up by coarse silt; however, and it also contains about 20-30 per cent of medium and fine-grain sand. For a certain type within this category the grain size distribution curve shows two peaks. Similarly, there exist sandy loesses having a mixture of coarse silt, fine sand and coarse sand with a single peak on the curve of the grain size distribution. This type of loess is mostly unstratified, calcareous, always more coarsely porous than the typical loess and has a similar colour. Varieties are sandy loess and loessy sand.

Brown loess:

(7) 5 m or thicker,

(8) thinner than 5 m,

(9) in discontinuous distribution.

This category is characterized by the predominance of coarse silt in grain size composition, its clay fraction below 2 microns is more abundant than in the typical loess; it is lime-free, with poor capillarity, colour is brown and in dry state brownish yellow (10 YR 6-7/4-8).

It is mostly of laminated structure. Varieties are loess loam, deluvial loess, slope loess, brown earth, limon à doublets, suglinok.

Loess derivate:

(10) in continuous distribution,

(11) in discontinuous distribution.

This is a collective name for those kinds of — mostly primary — loesses which were subjected to subsequent weathering and soil formation and suffered alterations. More clayey than loess, mostly lime-free or partly calcareous due to secondary calcification processes, compact or stratified, its structure is often prismatic or blocky, its colour is brownish, usually darker than loess, generally strongly spotted. Varieties are loess loam (Staublehm, Decklehm), gley loess, partly suglinok (in the Russian Plain), loess-like deposit (FINK, J. 1976; FINK, J. *et al.* 1977).

On the loess map of Europe this loess variety is interpreted, first of all, as an *in situ* (autochtonous) altered loess evolved under various paleogeographical conditions and processes. In my opinion, however, the loess derivate mapped for this category may occasionally be a syngenetic loess variety which never was loess since the conditions in the given site did not favour loess formation.

Loess derivate with detritus:

(12) in continuous distribution,

(13) in discontinuous distribution.

Grain size composition is variable, coarse silt fraction is present in 30-40 per cent, besides it sand, clay and sporadic coarse detritus are also typical, locally appearing in repeated thin layers.

This category comprises redeposited loess derivates with intermingled coarse detritus. Carbonate content is variable, locally lime-free, compact and stratified. This sediment is of darker tone than brown loess. Varieties are cryoturbational loess, solifluctional loess, mountain loess, detritic loess.

In my experience, detritic loess derivates do not only include the redeposited variety of loess derivates, but other kinds of transported loesses, intermingled with soil, sand or rock detritus can also be grouped with this category. Such loess derivates may occur independently or as individual or repeated horizons in a loess sequence. For this reason, occasionally, detritic loess derivates are also included in the loess sequence or among loessy deposits (redeposited loess and soil).

(14) *Loess-like flood-plain deposit*:

Sediment predominantly containing coarse silt with fine sand and clay content. In grain size composition 10-50 microns is the prevailing fraction, stratified or unstratified, occasionally more compact than loess, calcareous, with lower void ratio than loess and structure similar to loess. Close to groundwater table it has greyish yellow colour and spots. Synonyms are alluvial loess, infusion loess, lowland loess, bara loess (in Yugoslavia), baragan loess (in Romania).

It is wide-spread in the Middle Danubian Basin (the low plains of Hungary and Yugoslavia), but also common in the Lower Danubian Basin (in Romania). Radiocarbon age is 16 to 22,000 years (PÉCSI, M. *et al.* 1979a). It also occurs on the lower terrace of the Viennese Basin (Prater terrace) in smaller thickness (1 m) than in the Carpathian Basin, where it locally attains thicknesses to 2-4 m.

(15, 16) *Blown sand and cover sand*:

Grain size usually falls between 200 and 500 microns; unstructured deposit, which mostly builds up dunes or locally thin sand veneers.

Almost a hundred researchers contributed to the preparation of the loess map of Europe. Using the standard legend a sample map for Hungary was completed (PÉCSI, M. 1982, *Fig. 3*).

Loess chronology

Ice Age Calendar by Milankovitch, M. and the $^{16/18}O$ isotope stratigraphic time scale

During the last two centuries various theories have been set up to explain Quaternary glaciations and their cyclical recurrence. First ADHEMAR and CROLL assumed that the temporal changes in the elements of the Earth's orbit — in some combination, through indirect effects — influence climatic changes and the occurrence of glaciations on the Earth. Their calculations and conclusions, however, proved to be wrong in practice.

MILANKOVITCH calculated his radiation curve from the changing values of three parameters of the Earth's orbit — excentricity, precession and tilting of the axis of rotation. He based his theory on KÖPPEN's principle, i.e., the reason for or condition to glaciations is primarily the occurrence of cool summers and mild winters with high precipitation for a long period of time.

Over the past 600,000 years the 'cold' peaks of MILANKOVITCH's (1941) radiation curve rose above 'KÖPPEN's threshold value' on nine occasions, i.e., he provided a potential chronology for nine glacial periods with the precision of the calendar.

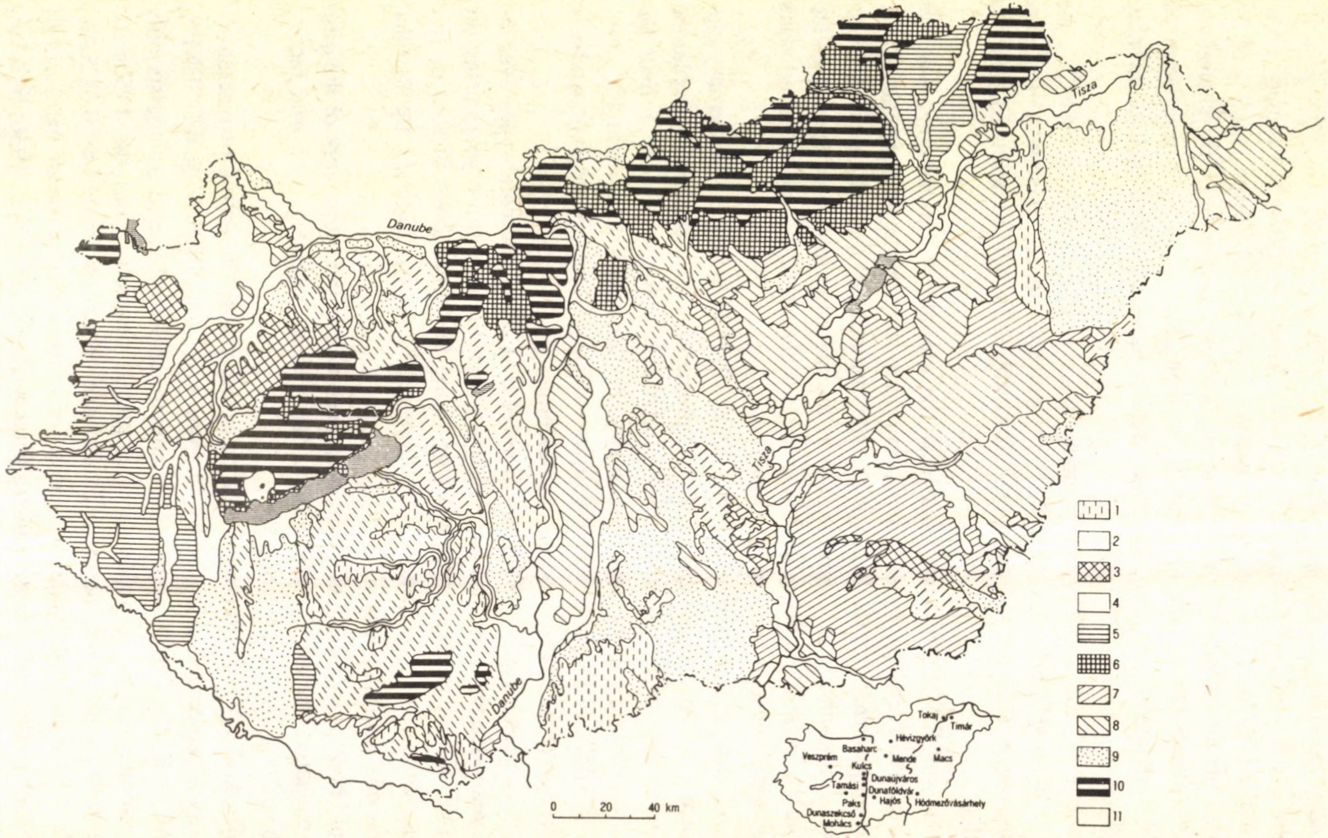


Fig. 3. The distribution of loess in Hungary (PÉCSI M. 1987c)

1 = typical loess; 2 = sandy loess; 3 = derasion loess (slope loess); 4 = brown loess in interrupted distribution; 5 = brown loess; 6 = loess derivates, loess lehm; 7 = alluvial loess-like deposits (infusion loess); 8 = holocene infusion loess; 9 = wind-blown sand; 10 = mountains; 11 = holocene fluvial deposits

He associated the last three glaciations (25,000, 72,000 and 115,000 years B.P.) with PENCK's *Würm* glaciation. The six earlier radiation minima were made to correlate with the *Riss*, *Mindel* and *Günz* glaciations *(Table 1)*.

Apparently, there showed some discrepancy between A. PENCK's ice age chronology and MILANKOVITCH's nine glaciations. PENCK doubted the validity of the ice age calendar set up by MILANKOVITCH and held the opinion that if the changes of the Earth's orbit were responsible for glaciations, then glaciations must have occurred also in the Tertiary and even before, since the changes in orbit parameters had probably been similar.

In defence of MILANKOVITCH and to dissolve the doubts of PENCK, the climatologist Gy. BACSÁK (1940, 1942, 1955) pointed out the existence of glacial oscillations during the Pliocene, but these radiation minima did not fall below KÖPPEN's threshold value.

Later it was BACSÁK who found that the climate of interglacials was not uniformly warm and even minor glaciations occurred in some of the interglacials. At the same time, he emphasized that the beginning of the formation of the individual ice-sheet is delayed some thousand years from the start of the radiation minimum (the so-called glacial cooling). Similarly the decay of the ice-sheet is also shifted some thousand years from the beginning of warm oscillations *(Table 2)*.

BACSÁK not only confirmed the MILANKOVITCH theory on Quaternary glaciation, but also developed it further, mostly supplementing its inadequately explained elements. The glacial and ice-free periods at BACSÁK do not simply reflect the alternation of warm and cold intervals, but actually, the alternation of four climatic types. Recently, M. BARISS (1989) pointed out that, instead of four, there were only two basic climate types; each of these can be strong or moderate.

There have been altogether 85 alternations of BACSÁK's climatic types over the last 600,000 years. He also detected these changes back to one million years using the PILGRIM table. During minor interglacials he found the alternations of four or five climatic types, while during the Mindel-Riss interglacial 29 units *(Table 2)* are included in his calendar of climatic history.

It should be kept in mind that, frequently, even within the framework of the orbit elements as causative factors for glaciations, the effects of certain terrestrial factors should also be taken into consideration.

The MILANKOVITCH theory on the causes and absolute dating of glaciations was at first only accepted and defended by climatologists (KÖPPEN, V. & WEGENER, A. 1924; BACSÁK, Gy. 1940, 1942). Astronomers criticized it and geologists only applied it sporadically for the subdivision of glacial deposits. Until the 1950s the chronological framework of the theory, defended and further elaborated by BACSÁK, was primarily applied in Quaternary research for correlations between members of loess-paleosol sequences and glacial or interglacial stages (SCHERF, E. 1936; BULLA, B. 1938; ÁDÁM, L. *et al.* 1954; KRIVÁN, P. 1953, 1955; MIHÁLTZ, I. 1953).

Since the mid-fifties the MILANKOVITCH–BACSÁK subdivisions of glacials was overshadowed by absolute dating methods such as radiocarbon, then by the paleomagnetic technique, deep-sea isotopic stratigraphy, foraminifer stratigraphy and other techniques. During the numerous research projects more and more data have accumulated to indicate that glaciations or cold climatic stages date back to much older times than 600,000 years (to ca. two or three million years). For some time these observations seemed to be contrary to the astronomical theory.

In their papers C. EMILIANI (1966), J.D. HAYS *et al.* (1976) — on the basis of isotopic and spectral analytical investigations of deep-sea boreholes — supported the MILANKOVITCH theory.

Thus, the alternations of Pleistocene glaciations and warm stages were primarily caused by changes in the excentricity, precession and rotation axis tilting of the Earth's orbit.

Naturally, Quaternary scientists have also been interested in what the oldest date is when the impact of a Pleistocene glaciation can be detected in terrestrial sediments.

Sedimentary sequences deposited over longer periods of time can be best studied in deep loess profiles, where numerous loess horizons are intercalated by paleosols.

The cyclical alternation of loess and paleosols have long been explained by cyclical climatic changes. It seemed obvious that the climatic history revealed from deep-sea boreholes should be compared with loess profiles (KUKLA, G.J. 1970).

The detailed analyses of the lithological and paleogeographical properties of loess sequences and their chronological correlation with deep-sea sediments gave a new impetus to loess and Quaternary research. At the same time, the intensive utilization and protection of loess regions called for more loess research of practical purpose.

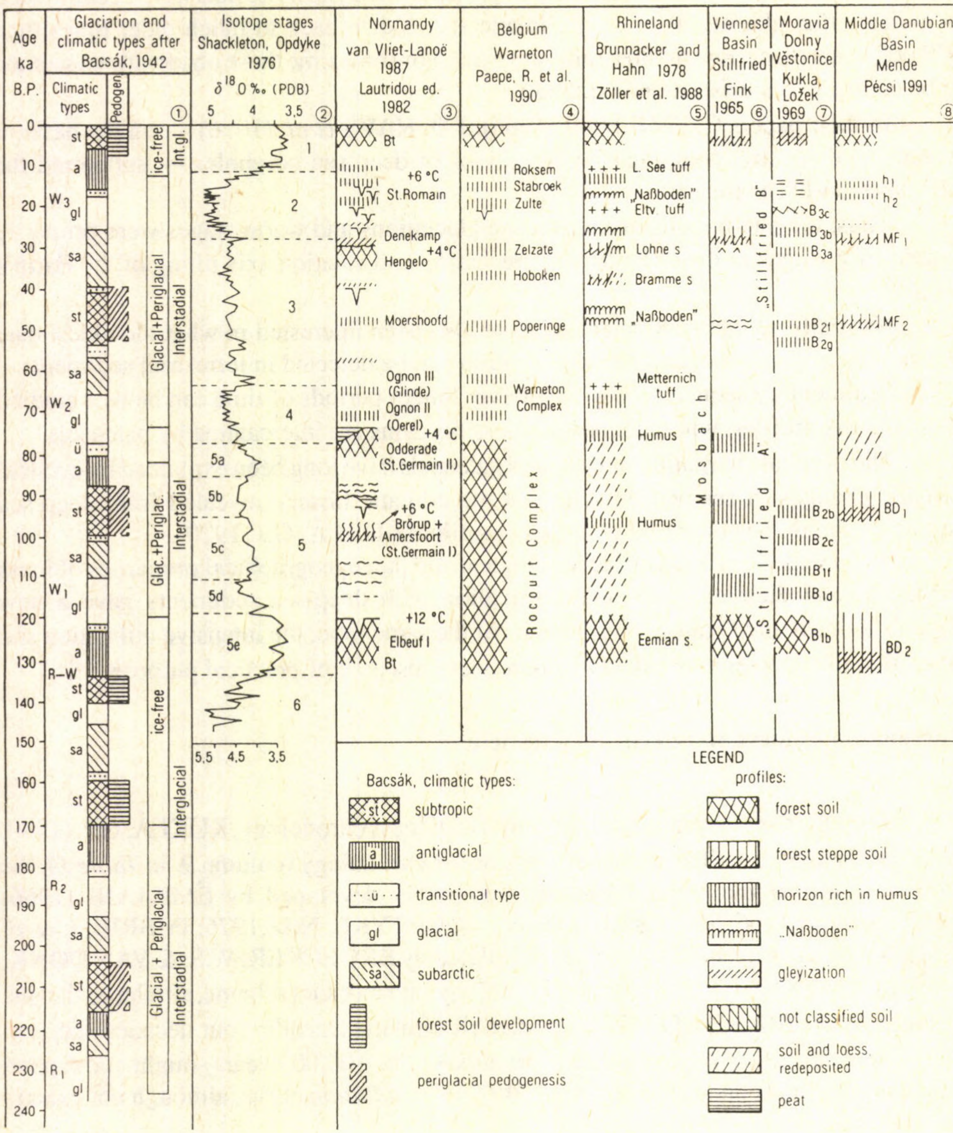
Correlation of loess and deep-sea sediments

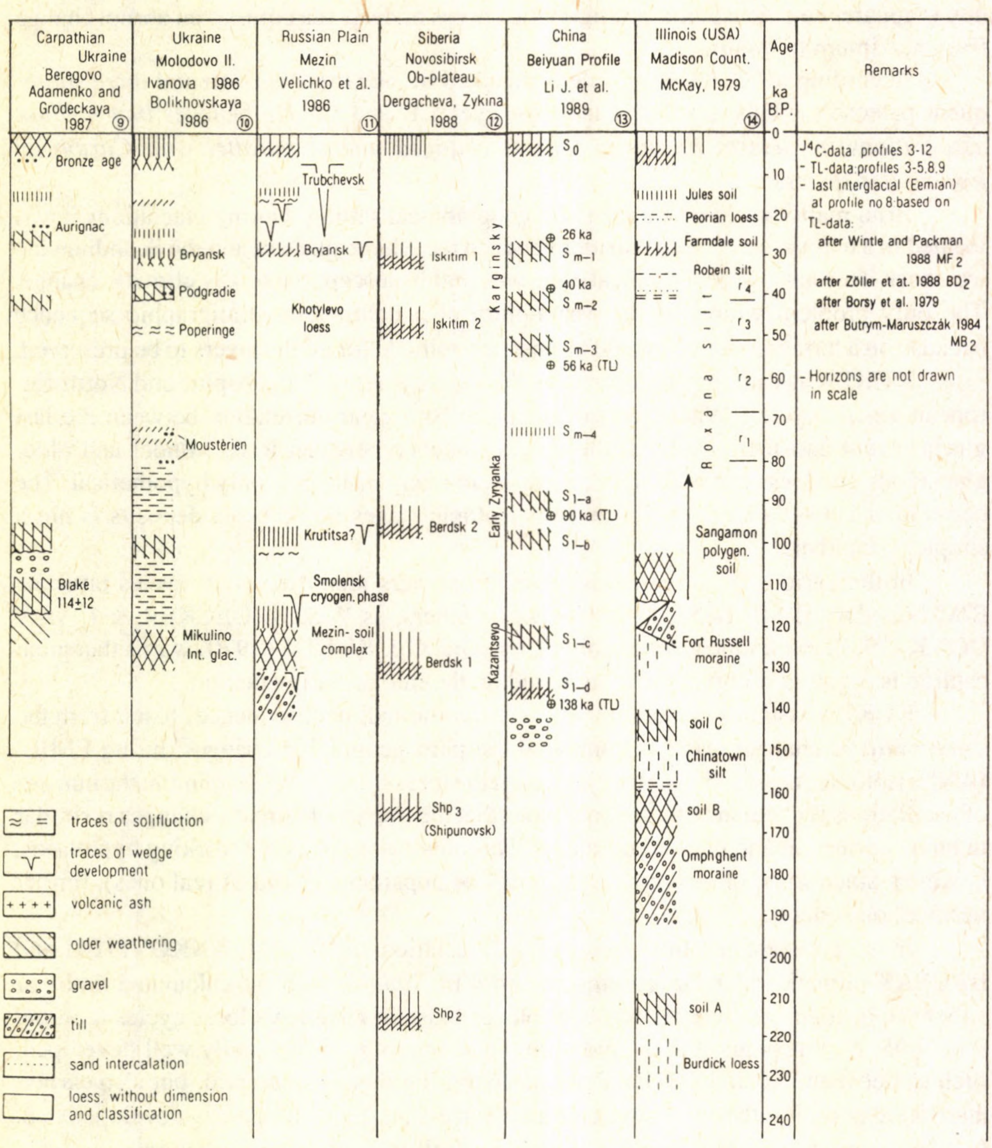
Since the early seventies, for the purpose of loess chronology, KUKLA, G.J. (1970, 1975, 1977) used, as a 'backbone' of Pleistocene chronology (column 9 in *Table 1)*, the isotopic stages of the oxygen isotope stratigraphy developed by EMILIANI (1966) (EMILIANI, C. 1966; SHACKLETON, N.J. & OPDYKE, N.D. 1976; IMBRIE, J. *et al.* 1984) as well as the *termination cycles* calculated by BROECKER, W.S. & VAN DONK, J. (1970). Thus KUKLA placed loess chronology into an exact scheme, similar to the one provided by the MILANKOVITCH–BACSÁK climatic calendar four decades ago.

The *intervals of* the individual *terminations* (ca. 100,000 years) might correspond to the amplitudinal changes of *MILANKOVITCH's radiation curve*, although not exactly with the same limits.

In KUKLA's (1970) opinion climatic changes can be reconstructed more precisely and in more detail from the terrestrial sequences of the Krems loess profile (Austria) and the Brno section (Czecho-Slovakia) than from deep-sea cores. He envisages a close parallelism between the chronology of the loess sequence and that of the deep-sea sediment sequence. In both sequences the location of the B/M boundary (0.73 Ma) can

Table 2. A tentative correlation of last glacial loess profiles





Carpathian Ukraine Beregovo Adamenko and Grodeckaya 1987 ⑨
Ukraine Molodovo II. Ivanova 1986 Bolikhovskaya 1986 ⑩
Russian Plain Mezin Velichko et al. 1986 ⑪
Siberia Novosibirsk Ob-plateau Dergacheva, Zykina 1988 ⑫
China Beiyuan Profile Li J. et al. 1989 ⑬
Illinois (USA) Madison Count. McKay, 1979 ⑭
Age ka B.P.
Remarks
Bronze age
Aurignac
Bryansk
Podgradie
Poperinge
Moustèrien
Blake 114±12
Mikulino Int. glac.
Trubchevsk
Bryansk
Khotylevo loess
Krutitsa?
Smolensk cryogen. phase
Mezin- soil complex
Iskitim 1
Iskitim 2
Berdsk 2
Berdsk 1
Shp 3 (Shipunovsk)
Shp 2
Karginsky
Early Zyryanka
Kazantsevo
S 0
26 ka
S m-1
40 ka
S m-2
S m-3
56 ka (TL)
S m-4
S 1-a
90 ka (TL)
S 1-b
S 1-c
S 1-d
138 ka (TL)
Jules soil
Peorian loess
Farmdale soil
Robein silt
Roxana silt
r 4
r 3
r 2
r 1
Sangamon polygen. soil
Fort Russell moraine
soil C
Chinatown silt
soil B
Omphghent moraine
soil A
Burdick loess
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200
210
220
230
240
14C-data profiles 3-12
- TL-data profiles 3-5,8,9
- last interglacial (Eemian) at profile no 8 based on TL-data:
after Wintle and Packman 1988 MF 2
after Zöller et al. 1988 BD 2
after Borsy et al. 1979
after Butrym-Maruszczák 1984 MB 2
- Horizons are not drawn in scale
traces of solifluction
traces of wedge development
volcanic ash
older weathering
gravel
till
sand intercalation
loess, without dimension and classification

be well established and the cyclicity is similar too. The number of glacial and interglacial formations is seven for each of both sequences. In the deep-sea cores the termination limits occur at about one hundred thousand year intervals where, in each case, a glacial thermal minimum suddenly turns into an interglacial thermal maximum. This phenomenon is apparent on the isotopic stratigraphic curves of deep-sea cores as an abrupt change from maximum to minimum.

According to KUKLA, a cycle is matched by one loess horizon and three subsequent paleosols. (This is valid at least for cycles B and C.) *He believes that mollusc associations in Central European loesses changed almost parallel with Caribbean foraminifer species.*

Brno really lies in a characteristic geographical setting. During glaciations it was located in a narrow periglacial corridor between the Alpine glaciers and the Scandinavian ice-sheet. This narrow geographical zone was highly susceptible to any climatic change. The only problem would be the assumption of a continuous stratigraphic sequence because on a terraced slope it would almost be a miracle for all the layers to be preserved.

KUKLA has attempted to correlate the loess cycles with the Alpine and North-European glacial cycles. Whereas there seems to be a clear correlation between the last glacial event and loess cycle B, the correspondence between Riss, Mindel and older glaciations and loess cycles C, D, E, F etc. is, in many instances, only hypothetical. The correlation between loess cycles and the isotopic stages of deep-sea deposits is not a simple task either.

In the various deep-sea cores some researchers identified eight cycles until the B/M boundary (EMILIANI, C. 1967), while others, as W.S. BROECKER & J. VAN DONK (1970) mark nine terminations. Therefore, G.J. KUKLA (1970) warns that great caution is required if correlations are based on the rate of sedimentation.

KUKLA assumes that continental and marine sediment sequences result from the same climatic changes. He has compared the paleogeographic changes during EMILIANI's isotopic stages 1-5 with the changes in the loess cycle B. In his opinion, the number of oscillations is equal in both. He concludes that the impact of climatic changes is similar in both continental and marine sediments. This concept is a feasible working hypothesis, however, since some of the coincidences can be apparent (instead of real ones), further verification is needed.

If we compare the time intervals of glaciations in the MILANKOVITCH and BACSÁK climatic calendar (columns 3 and 4 in *Table 1*) with the calculated limits of either the isotopic stratigraphy terminations or those of KUKLA's loess cycles (column 9 in *Table 1*), it appears that the individual glaciations are not equally well developed, such as between 240 and 400 ka. Particularly during this time interval, but also earlier, there were periods either without a continental ice-sheet or with a poorly developed one. In other cases the ice-sheet survived the warm spell following the glaciation.

Some problems concerning the comparison of δ ^{18}O isotopic stages and loess stratigraphy

Although the method of loess chronology based on the oxygen isotopic stratigraphy of deep-sea sediments seems to be an essentially correct one, today it has the following discrepancies:

1. The precise dating of oxygen isotopic stages is problematic in many instances.

2. The boundaries and durations of terminations from the older stages (14-16) can be remarkably different.

3. In the sediments of the North-Atlantic ocean the foraminifer group *Globigerina menardii*, indicating cold environment, is not present in the layers older than the isotopic stage 16 (ca. 570 ka). It is significant that the cold peaks in stages older than the Jaramillo event (0.9 Ma) are remarkably weaker in their developments than in the case of stage 14 and the younger.

4. Downwards from stage 17 and particularly from stage 24 the fluctuations of the oxygen isotopic curve, that is, the amplitudes of crenulations are becoming gradually weaker and their potential to provide information is reduced.

5. The concept that the major 'cold' peaks of the oxygen isotopic curves and their secondary minor peaks reflect the oscillation of global ice-sheet (IMBRIE, J. *et al.* 1984; SHACKLETON, N.J. & OPDYKE, N.D. 1973, 1976; BROECKER, W.S. & VAN DONK, J. 1970) will probably receive further supporting evidence in the future. Concerning the isotopic peaks which indicate the volume of ice, two considerations seem to be appropriate:

a) From a physical-meteorological viewpoint, the atmosphere is more susceptible to changes in the amount of radiation received by the Earth than ocean water. This may also apply to the changes of the volumes of ice-sheets.

b) If the ice-sheet did not reach beyond latitude 68°, though it can still be considered a large one, it did not cause a 'glacial' phase (MILANKOVITCH, M. 1930; BACSÁK, Gy. 1942; KÖPPEN, W. & WEGENER, A. 1924). When on this latitude the radiation did not reach the threshold value of KÖPPEN no 'true glaciation' could develop. The shift of climatic zones was only moderate on the Earth and glaciation was restricted to high mountains and polar ice-caps. The oxygen isotopic curve verifies this for marine sediments, but in the continental zones the conditions for soil and sediment formation differed from those when ice-sheets extended south of latitude 68°.

6. At any rate although the application of oxygen isotopic stratigraphy appears to be a useful technique in the chronostratigraphy of subaerial loess, further data and comparisons are still needed, particularly in the case of older stages and loess cycles. Such comparisons are also to be made with MILANKOVITCH's climatic curve and with the sequence of climatic types calculated by BACSÁK, as well as with the absolute chronology in the climatic calendar (columns 3, 4 and 9 in *Table 1*).

7. The identification of the age and duration of the individual stages in oxygen isotopic stratigraphy through interpolation is only possible if one relies on some 'fixed' data (such as the B/M boundary, the Barbados coral at 120 ka) and the estimated rate of sedimentation. It is well known that there is also uncertainty in identifying these data as well as in delimiting the stages of deep-sea cores (KUKLA, G.J. 1977; RUDDIMAN, W.F. *et al.* 1986). Cumulative error for the older stages may exceed the duration of a whole stage or even of a termination period.

8. In the comparison of loess and paleosol sequences with deep-sea isotopic stratigraphy one should also consider the fact that erosional hiatuses are more frequent and extensive in the continental sequences.

Even for profiles located not far from each other it is a common phenomenon to have different numbers of loess horizons and paleosols in the profiles compared. Thus, for instance, in the profile of the Paks brickyard there is considerable variation within a 100 m distance. It is a general situation that the number and spatial position of loess and paleosol horizons are not identical even within the same loess region.

Other problems in loess chronology

Paleomagnetic investigations are mostly only able to provide a safe date for the Brunhes-Matuyama boundary (0.73 Ma). Anomalies or events (Blake 0.127 Ma) in young loesses or polarity changes expected in the bottom horizons of old loess are only recognized very seldom or through very circumspective analysis. Therefore, the determination of the B/M boundary provides very important information for the entire loess chronology.

1. Field observations do not always provide satisfactory means to decide whether a single loess pocket developed *in situ* or was redeposited. In the actual cases it is also difficult to say whether a given paleosol is a redeposited one. Neither is it clear whether neighbouring pairs of paleosols (double paleosol or soil complex) formed in the same interglacial or interstadial and only separated by a small amount of intercalated and redeposited loess or there is a major sedimentation gap between the two paleosols. In the latter case the two paleosols represent two different interglacials.

2. Views exist that the *radiocarbon* dating of *charcoal* found in loess is only reliable for the last 30-40 ka.

3. For the time being, there is much debate about the various thermoluminescence dating techniques. The TL datings of the same loess pocket may be rather different if different methods are applied and one laboratory may produce data twice as old as the other one. Every TL laboratory naturally believes in the reliability of their own data. TL datings based on insufficient random sampling are not convincing and the analysis of complete profiles is necessary.

Subdivisions of young loess

The role of loess profiles in the subdivision of the last glacial

In loess sequences multiple changes of paleoecological conditions (organic life, physico-chemical processes) can be detected for longer periods. The best opportunity to study paleoclimatic and paleoecological changes is provided by the loess sequence from the last interglacial period which can be investigated through almost complete profiles in many places. It has to be noted here that loess formation has not been continuous in every loess region over the last glacial period (ca. 117-10 ka B.P.). In some geographical zones the loesses were formed only during the maximum (24-12 ka B.P.) and late stages of the last glaciation. During last glaciation loess formation was interrupted and in some subzones or regions the evidence of soil formation, or traces of it, can be found.

The last interglacial soil can only be dated now — on a global scale — by indirect methods. Significant paleomagnetic data and reliable TL datings are few. There are difficulties with the precise absolute dating of loess and paleosols developed in the first half of the last glaciation. There may be differences in the number and types of loesses and paleosols in young loess profiles between different regions and, therefore, their correlation can only be approximative *(Table 2)*.

Paleogeographic reconstruction for last glaciation based on loess profiles

During the last glacial event in Central and Eastern Europe (columns 3-8 in *(Table 2)* four to six loess layers and four to seven intercalated humic loess, humic steppe soil and locally peaty tundra soil occur, while in Eastern Europe and Siberia the number of loess and paleosol units seems to be smaller. The young loesses of the Great Plains along the Mississippi are less subdivided than those in Central Europe *(Table 2)*.

It was found that the cyclical changes of deep-sea oxygen isotope stages ('warm-cold') are closely correlated with the MILANKOVITCH theory, i.e., the cyclical alterations of radiation (BERGER, A. *et al.* 1984). Over the last 130 ka the oxygen isotopic stages and substages mark altogether 12 warm-cold climatic periods of various duration in the deep-sea cores.

In MILANKOVITCH's (1941) calculations the geographical zones of the Northern Hemisphere are more directly affected by the fluctuations of solar radiation. According to BACSÁK's calculations, the climate types changed 18 times during the last 130 ka. They include four relatively short transitional types, which are probably not reflected in the loess sequences. In some young loess profiles studied in detail the number of lithostratigraphical units pointing to warm and cold phases reaches or even surpasses the number of climate type changes established by BACSÁK *(Table 2)*.

Based upon the data of M. MILANKOVITCH (1930), M. BARISS recently (1991) reinterpreted BACSÁK's (1940) four climate types. As mentioned above, BARISS suggested two basic climate types: oceanic or continental, each of them can be strong or moderate. On BARISS' curve at the 55° N latitude a moderately continental type of climate occurred in the period of 65 to 28 ka B.P. during which summers were moderately warmer and winters moderately colder than those of today (± 1°-2° C range). Apart from this particular time period, BARISS' curve seems to indicate a sort of 'transitional' climatic situation at about every 10-20 ka where a continental climate type changes into an oceanic type, or vice versa, when the summers and winters had about the same temperatures as those of the present. Around these transitional phases minor erosional hiatuses are observed in the loess profiles. Their further investigation and inventory appear to be necessary.

1. For the identification of the *duration* and subdivisions of *last glacial cycle* numerous attempts have been made. Although the different time-scales are recently being correlated to each other, from the viewpoint of the paleogeographical reconstruction of young loess-paleosol sequences, the difference of time-scales, eg. between the $\delta^{18}O$ isotope stages (2-5) and the glaciated and ice-free stages by Milankovitch, is evident. The most important discrepancy is found in the time-span of last interglacial (R/W or 5e) and its place on the time-scale.

On the Milankovitch and Bacsák time-scale R/W interglacial can be placed in the interval between ca. 140 to 120 ka B.P.,[1] while the stage 5e is dated 128 to 116 ka B.P. *(Tab. 2)*. The two time-scales, frequently applied for loess-paleosol stratigraphy indicates a shift of ca. 20 ka for the date of last interglacial. If the longer interval is assumed for R/W interglacial, the formation of polygenetic soils is more easily interpretable.

The difference between the duration and position on time-scales of oxygen isotope stages 2 and 4 and stadials W_2 and W_3 does not seem to be more than 5,000 years. The prolonged interstadial (66 to 26 ka B.P.) between two glaciated stages allowed sufficient time for the formation of double or storeyed soils, the younger of which (29 to 25 ka B.P.) is of almost world-wide distribution.

The most widespread and thickest young loess layers date to stadial W_3 (i.e., oxygen isotope stage 2), between 24 and 12 ka B.P. Under the prevailingly glacial climate of this period cool-humid and cold-dry spells alternated. Until the beginning of the Holocene only poorly-developed humous arctic soils (2-3) formed in the periglacial loess zone.

2. *The paleoclimatic reconstruction of last glacial cycle* is hindered by variation between key sections (differing numbers of paleosol layers and loess horizons, paleocatena variation and hiatuses). Therefore, either a general reconstruction can only be given or it has to be based on a particular loess-paleosol profile which includes most of the stratigraphic units present in key sections.

[1] The isotope temperature curve for the Vostok station shows strong warming in a very similar period.

In each case a fundamental task is to identify last interglacial soil. Because of the few and uncertain absolute datings, this is only possible even now through the use of comprehensive, indirect approaches.

With some restrictions we assume that in the selected type localities *(Table 2)* last interglacial soil is identified.[2] With this in mind, the general statement can be made that in most of the key profiles between the last interglacial and the recent soils there are 5 or 6 (two or three poorly-developed) paleosols and 5 to 7 loess or sandy loess horizons. In the layers mentioned and between them — especially in the former periglacial zone — severe cold climate is indicated by *permafrost pseudomorphs* in 3 to 5 levels (*Table 2* — columns 3, 4 and 11).

In addition, in some loess regions (such as in Eastern Central Europe, North America, Columbia Plateau and the Tashkent loess in Central Asia) *buried dells* in two or three levels are observed in the last glacial loess. Dell development could take place in cool-moist climatic spells, simultaneous with the formation of embryonic soils.

The number of climatic phases which can be reconstructed from the mentioned loess-paleosol sequence and the enclosed phenomena (dells, cryoturbations, solifluction and erosion) of climate-indicating role is 16 to 20. These can be interpreted as there happened at least 16 to 20 changes in the climatic conditions necessary for the development of the mentioned layers and phenomena over the time span when the young loess-paleosol sequence came about (130 to 10 ka B.P.). These climatic phases of 2 to 10 ka duration[3] are partly composed of climatic oscillations of shorter duration and partly formed higher-rank cycles of 20 to 40 ka length; on three occasions stadial and interstadial and on one occasion interglacial paleoenvironments recurred, excluding the Holocene.

3. The sequence of some loess profiles may be *quasi-complete*, embracing a sequence from last interglacial to our days. Still, according to their paleoenvironmental positions, they show variation of various scale in their sequences. For an approximative reconstruction of climatic changes — in our opinion — a particular sequence of a loess region has to be investigated, paying due attention to results obtained from similar profiles in the area under study *(Fig. 4,* PÉCSI, M. 1992*)*.

4. Within some loess regions young loess mantles may occur which formed exclusively during last stadial, W_3 (26 to 12 ka B.P.). In such loesses — which can attain

[2] In the opinion of some of the researchers, the last interglacial soil formed over a longer time span of warmer and moister climate and it is better developed than the present-day surface soils or other paleosols in young loess (FINK, J. 1974; GERASIMOV, I.P. 1973). The statement that last interglacial soil is of the same nature than the recent soil in the given locality (BRONGER & HEINKELE 1989) is an oversimplification of reality or founded on a misinterpretation of nomenclature.

[3] Called climatic types by BACSÁK (1942) and climatic phases by KUKLA and LOŽEK (1961), these units were repeated 3 times 6 equals 18 occasions during the last interglacial/glacial cycle. The temperature curve reconstructed from palynological data from Grand Pile (WOILLARD 1978), Les Echetts (PONS *et al.* 1989) and Washington State (HEUSSER 1972) also allows conclusions for 17 to 19 climatic changes or oscillations during the last glacial cycle.

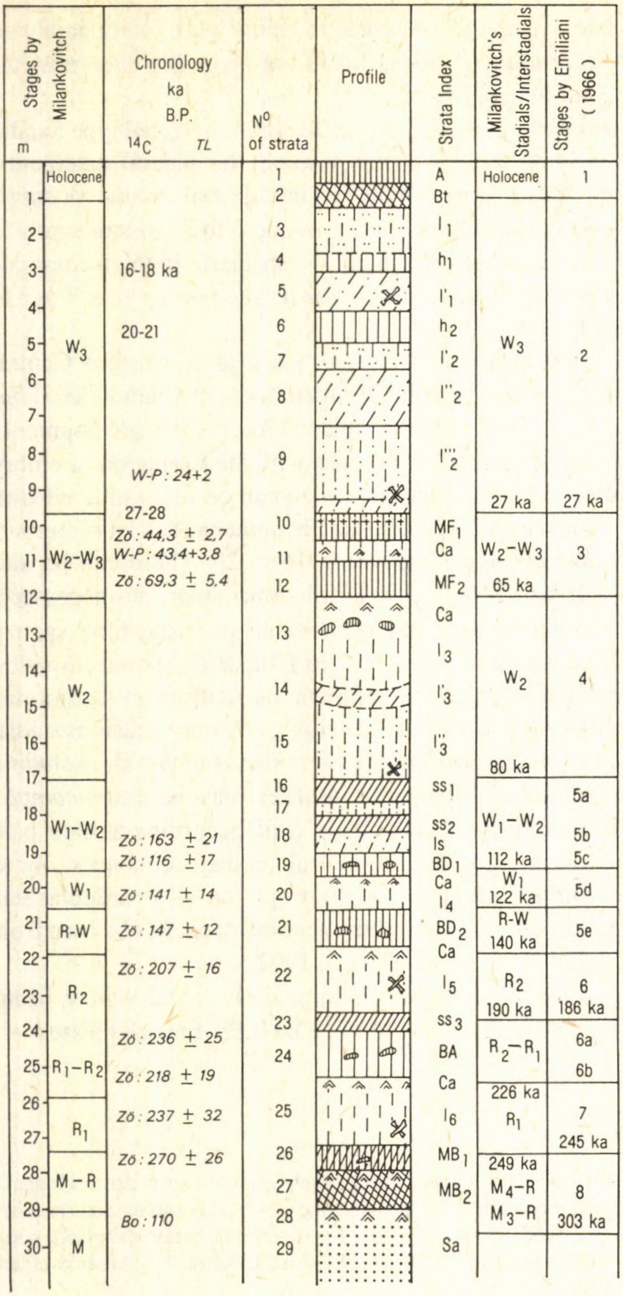


Fig. 4. Litho- and chronostratigraphy of the loess profile at Mende in Hungary (reconstruction of cyclical climatic changes on the basis of events in the loess-paleosol sequence, according to PÉCSI, M.) ^{14}C data: Lab. Hannover; TL dating: Bo = BORSY *et al.*, 1979; W-P = WINTLE and PACKMAN, 1988; Zö = ZÖLLER, L. 1989-1991; Magnetostratigraphy: MÁRTON, P. 1979; PEVZNER, M.A. 1979-1990; many samples of the profile were investigated and only normal polarity was found

thicknesses up to 4-10 m — only embryonic soils, two or three humic loess horizons, cryoturbational phenomena and dells filled by sandy loess occur (MAROSI, S. & SZILÁRD, J. 1988; PÉCSI, M. 1982).

5. *It may not be accidental that the number of loess-soil-sand layers formed during the last glacial cycle is close to or identical with BACSÁK's climatic type varieties or the possible repetitions of KUKLA's phases.* From the analysis of young loess sequences in the profiles of Western and Central Europe it can be assumed that during a single climatic or a sedimentation phase only one (or rarely two) stratigraphic unit formed. Over the longer periods a cyclicity can be observed in sedimentation, but erosion gaps could also develop.

Fig. 4.

1 = chernozem, steppe dynamics, afforestation in the late Holocene, cultivation, soil erosion, dell (dry valley) infilling; 2 = brown forest soil (B_t); 3 = sandy loess formation (l_1); 4 = loessy humus (h_1), embryonic soil, taiga parkland with charcoal of *Picea, P. cembra*, and of dell infilling; 5 = sandy loess (l'_1) with reindeer remnants, dell incision and infilling, permafrost; 6 = loessy humus (h_2), embryonic (arctic) soil, taiga grove, charcoal; 7 = sandy loess (l'_2); 8 = dell loess (l''_2), dell incision and infilling with residual permafrost; 9 = sandy loess and typical loess (l'''_2), complete skeleton of *Elephas primigenius*; 10 = steppe soil (MF_1), cold-steppe taiga groves with much charcoal of *Larix, Picea* and *P. cembra*; 11 = thin loess, strong carbonate accumulation under MF_1 soil, erosional hiatus; 12 = better-developed grove steppe soil (MF_2) with charcoal (*Picea*). The paleosols MF_1 and MF_2 are not identical with the present-day soil on which the original association was *Prunetum tenellae* or *Acereto tatarici-Quercetum*; 13 = thick, triplicate loess horizon (l_3); 14 = dell loess, slope loess (l'_3), dell incision and infilling; 15 = sandy loess (l''_3), remnants of *Elephas primigenius*; 16 = semipedolite, soil sediment (ss_1), slope wash and solifluction; 17 = sandy loess (l''_3); 18 = semipedolite, soil sediment (ss_2), and solifluction loess (l_s); 19 = steppe soil (BD_1), with *Betula, Pinus* and *Artemisia* pollen (URBAN, 1984); 20 = sandy loess (l_4); 21 = steppe soil (BD_2) with medium carbonate accumulation, predominant pollen are *Pinus, Betula* and *Artemisia* (URBAN, 1984); 22 = loess (l_5), remnant of *Elephas primigenius*, probably belonged to Riss 2 glacial stage; 23 = soil sediment (ss_3), slope wash and steppe soil formation; 24 = steppe soil formation (BA) with a strong carbonate accumulation horizon, predominant pollen are *Artemisia* > *Cerealia* typ (URBAN, 1984), warm temperate climate, moderately dry steppe condition; 25 = loess (l_6), remnant of *Equus* sp., probably Riss 1 glacial stage; 26 = steppe soil formation (Mende Base, MB_1), with many krotovinas, this part of the soil complex probably developed during a transitional steppe climate between mediterranean xerophile brown forest soil and loess steppe conditions; 27-28 = brown forest soil (MB_2) with $CaCO_3$ nodules in the Bt horizon and very strong Cca horizon with big loess dolls (28), in MB_2 the predominant pollen are *Pinus* > *Picea, Chenopodiaceae* (URBAN, 1984), warm temperate climate with dry and wet seasons; the MB paleosol complex probably developed during the upper part of Mindel-Riss interglacial stage; 29 = proluvial sand, TL dating is a minimum age, however, underestimation is possible. The TL ages of the paleosols BD_1 and BD_2 seem to be somewhat too high since these values — according to the different time-scales —indicate stadials instead of interstadials. A somewhat similar problem of calculation exists with the age determined by ZÖLLER for the paleosol MF_2. Both by the SPECMAP time-scale and by the MILANKOVITCH time-scale, climate was cold between 59,000 and 71,000 years B.P. Consequently, these periods were less suitable for soil formation

Loess of China

Loess stratigraphy

Several lithostratigraphical regions can be identified on the Loess Plateau. The profiles most suitable for the stratigraphic subdivision of the loess are located in the middle and W of the Plateau, in the vicinity of Luochuan, Xifeng and Lanzhou. Relying on information from Luochuan and Xifeng and several other profiles the whole sequences of Chinese loesses (L) and paleosols (S) were estimated — by paleomagnetic measurements — as 2 to 2.5 million years old (LIU, T. *et al.* 1985) and referred the following to five typical subgroups:

1. Potou loess	1.5-2 m	Holocene (L_o, S_o);
2. Malan loess	10 m	Upper Pleistocene (L_1, S_1);
3. Upper Lishi loess	30 m	Middle Pleistocene (L_2-L_4, S_2-S_4);
4. Lower Lishi loess	50 m	Middle Pleistocene (L_5-L_{15}, S_5-S_{14});
5. Wucheng loess	50 m	Lower Pleistocene (W_{L1-4}, W_{S1}-W_{S4})

The last one overlies subaerial red clays (of 5-40 m thickness) in many places.

Recently, the Brunhes-Matuyama boundary (0.72 Ma) was found in the exposures and boring logs of Luochuan in paleosol S_8 or in the overlying loess (L_8). In the exposure of Xifeng this boundary was found in L_8. Beyond this similarity in the results, there are also differences between the loess sequences of the two localities (SASAYIMA, S. 1984; LIU, X. *et al.* 1985; KUKLA, G.J. 1987).

The *Matuyama-Gauss boundary* (2.4 Ma) was placed at the contact of the Wucheng loess and red clays.

The comparative studies in the loesses of Luochuan and Xifeng support the conclusion that even from (entirely) continental-subaerial sedimentary sequences, it is possible to verify all the glacial and interglacial stages of the Pleistocene (LIU, X. *et al.* 1987; LIU, T. & YUAN, B. 1987).

In the Luochuan and Xifeng profiles the absolute age and duration of development have been established by several researchers for each loess horizon (glacial interval) and paleosol (interglacial interval) through simple interpolation. Additional calculations were made on the deposition rates of the loess horizons, magnetic susceptibility curves were prepared and major magnetic polarity changes were identified.

Based on these computations, the results of the loess and paleosol dating on the Loess Plateau of China are shown in the attached *Table 1* and *2*, also presenting comparisons with deep-sea isotope stages.

Some problems of the chronological evaluation of the Chinese loess sequence

Concerning the chronostratigraphical subdivision of the Loess Plateau, in the most often cited Luochuan and Xifeng loess profiles, the so-called Malan loess (L_1) mostly occurs in the horizons down to the first paleosol (S_1), without further subdivisions. In these profiles the first paleosol (S_1) is supposed to represent the last interglacial (LIU, T. *et al.* 1985; KUKLA, G.J. 1987). Comparing these papers with my field observations, I have found the contradiction (PÉCSI, M. 1987a) that, on the Loess Plateau, last glacial (Malan) loess would include less intercalations than the young loesses of Central Europe *(Table 2)*.

This contradiction seems to be resolved by the Beiyuan loess profile on the second terrace of the Daxiahe river, near Lanzhou (LI, J. *et al.* 1989), where the Malan loess preserved probably the whole loess and paleosol sequence of the last glaciation.

In the Beiyuan loess profile the Malan loess series is ca. 28 m thick subdivided by six paleosols, and all these together represent the last glaciation *(Table 2)*.

In the above mentioned key profiles of the Loess Plateau of China the checking of the presence of the assumed complete sequences is also an important task. Anyone dealing with the character of terrestrial deposition has problems to imagine that no major sediment hiatus, at least in some horizons, would occur in the case of a plateau that has been raised, continually or spasmodically, to more than 1,000 m above sea level for about 2.5 million years. No perfect sediment trap can be assumed in a basin with drainage network, slowly or periodically subsiding, and it is known that sedimentation gaps are observed even in deep-sea cores. Taking all these into account, the procedure by which the peaks of the susceptibility signals of the 2.4 million year old and 130-200 m thick Loess Plateau sequence, assumed to be quasi-complete, are correlated with the sequence of oxygen 16/18 isotope changes in deep-sea deposits has to regarded largely oversimplified.

In the various partial basins of the *Loess Plateau of China* of more than 1,000 m altitude the thickness of loess series and the number of paleosols show great variation.

The Xifeng profile differs from the Luochuan one, located 160 km to the east. Nevertheless, the sequences are generally regarded identical (LIU, T. 1987). For both type profiles in the major upper part 14 paleosols and 15 loess horizons are identified. The B/M paleomagnetic boundary is placed below the paleosol S_7 in the Xifeng profile and in loess L_8 in the Luochuan profile.

The subaerial sequence cannot easily be subdivided into loess and paleosol layers below sandy loess L_{15}, but clusters of layers with weathering or soil formation of various intensity alternate. This is the so-called *Wucheng loess*, which includes 4 more pedified clusters of layers (W_{S1}-W_{S4}) and 4 clusters of loessy-loamy layers (W_{L1}-W_{L4}) in the Xifeng profile. In the Luochuan profile these divisions are only repeated three times. The paleomagnetic analyses, however, support the interpretation that in both profiles the red clays in the base of the Wucheng series belong to the Gauss epoch. The Olduvai event within the Matuyama epoch (1.67-1.87 million years B.P.) was found in the paleosol group W_{S2} in the Luochuan profile and in W_{S3} in the Xifeng profile.

In the above two key sections of the Loess Plateau of China — at Luochuan and Xifeng — 24 and 28 loess horizons and an equal number of paleosols are counted, respectively. In a recently analysed profile — at Baoji — the alternation of 32 paleosols and loess horizons has been recorded (DING, Z. *et al.*, 1991).

From the data of paleomagnetic investigations, calculation of sedimentation rate, analysis of magnetic susceptibility curves and comparisons with oxygen isotope stages in deep-sea cores, it was established that by the evidence provided by the profiles of the Loess Plateau of China all the glacial and interglacial periods during the Pleistocene can be identified in the subaerial sequences (LIU, T. 1987; LIU, T. & YUAN, B. 1987; KUKLA, G.J. & AN, Z. 1989).

On the basis of the stratigraphical works dealing with the Loess Plateau and of the experience gathered during my three field trips with Chinese and other foreign specialists, I have been convinced that, as compared with other places, the Chinese loess profiles exhibit the most detailed stratigraphic subdivisions. Besides, the most complete reconstruction of the climatic changes which took place during the Quaternary should be expected from the thorough analyses and comparisons of profiles from the Loess Plateau of China.

Loess in Hungary

Loess-like deposits on the low alluvial fans of the Great Hungarian Plain

In Hungary the so-called *infusion loess* is of the widest distribution as it mantles the Tisza plain, the broad flood-plains of rivers without valleys and the surfaces of alluvial fans, which only rise some metres above the flood-plain level. Thickness of this loess ranges from 0.5 to 5 m.

The grain size composition of the infusion loess is highly variable as occasionally the sand fraction becomes dominant, while in other places clay fraction becomes the next in prevalence after silt. Carbonate content is considerable (10-20 per cent). In the profiles of this infusion loess there are paleosols of meadow type with clayey loam texture and low carbonate content (5-10 per cent).

According to the results of investigations in the Radiocarbon Laboratory of the University of Helsinki, the formation of infusion loess took place 24,000–18,000 years ago.

The so-called '*lowland loess*' always lies by 5-10 m higher than the infusion loess. The fundamental difference between infusion and lowland loess is that while the former one is only 2-5 m thick, the latter one reaches 50 m thickness and is subdivided by numerous paleosol and sand layers. Among paleosols chernozems are common, but forest soils and, in the bottom part of the loess series, red soils also occur. The thick loess-soil-sand series of the lowland loess has reached its position below the present base level of erosion during the subsidence of the Great Plains (MIHÁLTZ, I. 1953; MOLNÁR, B. 1966, 1970; RÓNAI, A. 1985).

Loess in hill and foothill regions

The minutely dissected hills and foothill surfaces of Hungary are mantled by thick loess. As opposed to infusion loess at the flood-plain level, this loess was also called *'dryland loess'*. There are numerous varieties, both for grain size composition and origin. The varieties are usually well separated not only in space but also distinct in the individual profiles. Loess, loess-like sediments, stratified sandy loess, sand and paleosols alternate.

In the Transdanubian Hills, particularly on slopes and in minor valleys, *valley loesses*, stratified parallel to the slope are characteristic (LÓCZY, L. sen. 1913). Their varieties are considered under the collective term of *'derasion loess'*.

The top series of the derasional loesses in the hilly regions belong to the so-called young loess group. The total thickness of loess in hill regions exceeds 50-60 m locally.

In the exposures of foothills the loess is usually not older than the last glaciation. Locally it is even possible to find some very young loess which is sandy, detritic, stratified and 10-20 m thick *(Fig. 4)*.

Loess on higher alluvial fans and river terraces

On the major alluvial fans of the Great Hungarian Plain sand, sandy and typical loess alternate as surface sediments. Where the sand is only covered by some metres of sandy loess, the transition between the two layers is usually gradual. The underlying sand is mostly wind-blown, but fluvial sands overlain by thin veneers of loessy sand and sandy loess with poorly defined boundary also occur (BORSY, Z. *et al.* 1969).

On the flood-free terraces of the Danube and some of its tributaries — in a fortunate geomorphological position — almost complete sequences of young loess have been preserved with 4-5 well-developed forest steppe soils.

The profile studied in most detail, which became a classic exposure in Hungarian and international Quaternary literature, is the 50 m deep loess section of the Paks brickyard *(Fig. 1)*. The exposure of the quarry does not reach the bottom horizons of old loess series which can be seen in the Dunaföldvár exposures *(Fig. 5)*.

On the Great Plain, along the Danubian bluff, the loess exposures in the vicinity of Paks and Dunaújváros *(Figs. 1, 5)* provide useful information not only for the loess stratigraphy in Hungary but also for that in Europe and also, promote the subdivision of the Quaternary.

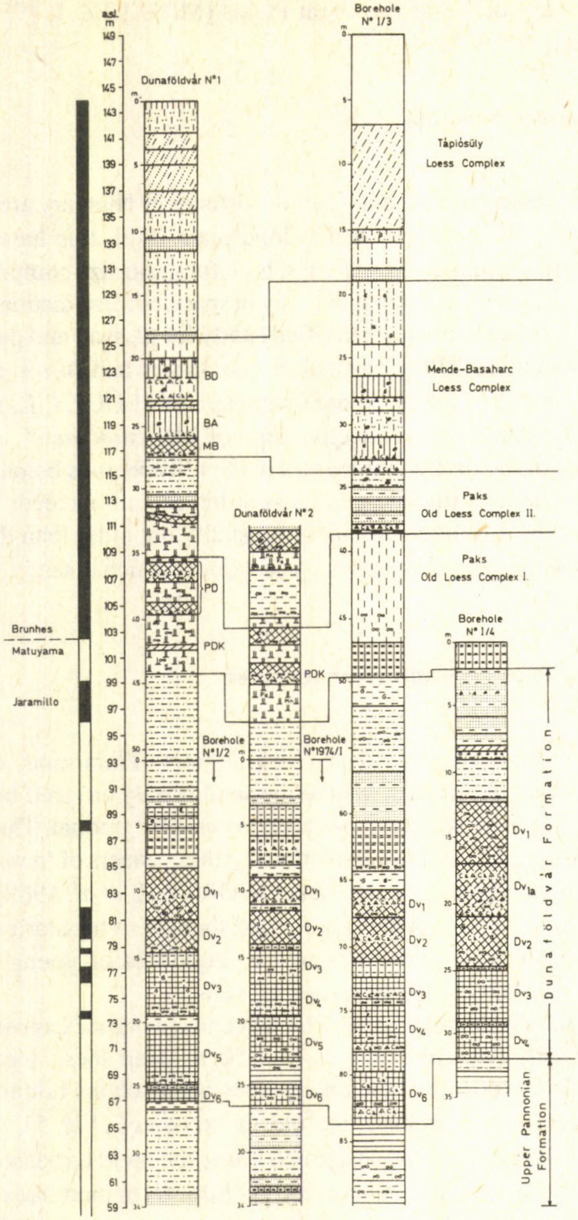


Fig. 5. Subdivision and correlation of loess profiles at Dunaföldvár

Dunaföldvár formation underlying the young and old loess series contains mainly sequence of reddish paleosols (Dv_1-Dv_6) meadow soils and sand, silty sand

Loess stratigraphy for Hungary

Upper part of the young loesses (Dunaújváros-Tápiósüly series)

The most complete known section of the young loesses is ca. 10 m thick and mostly consists of layers of sandy loess and loessy sand. There are only two intercalated, poorly developed soils (or humous loess horizons) (h_1, h_2 - *Fig. 4*).

In the top part of the first humic layer in the Tápiósüly profile *Pinus cembra* and *Larix* charcoal remnants occur. Their radiocarbon age is 16,730 ± 400 years. In the loess, (l_1) above the humic layer (h_1) there are abundant though sporadically distributed *reindeer* bone remnants. This loess horizon with reindeer remnants appears in similar stratigraphic positions in several profiles.

Dating the charcoals found in the Dunaújváros profile, the age of the older humic soil (h_2) was determined as 22,000–20,000 radiocarbon years *(Fig. 4)*. The lower sandy loess (l_2) frequently contains mammoth bones.

Judging from the texture of the layers, in the accumulation of the upper part of the young loess series in Hungary — in addition to falling dust — wind-blown sand movements and solifluction caused by meltwater flow also played a part.

The analysis of the profiles indicated that during the period of formation of the *upper young loesses* (ca. 26-12 ka) three sandy loess layers (l_1, l_2', l_2'') developed which are separated from one another by two humic loess horizons (h_1, h_2) as well as by layers of loessy sand with dell fill (l_1) and sandy loess (l_2). Both humic loess horizons (h_1 = 16-17 ka and h_2 = 20-21 ka) are considered products of arctic soil formation. Before their formation the processes of dell deepening (slight erosion) and then dell filling (sparse vegetation and solifluction) took place.

Tentative dating of the lower young loesses (Mende-Basaharc loess series)

This series of three or four major loess layers and four paleosols is about 15-20 m thick *(Fig. 4)*. In some cases the paleosols are overlain by pedosediments or loessy semipedolite.

The *Mende Upper* (MF) paleosol is usually a double layer. The top part (MF_1) is poorly developed chernozem with animal burrows and charcoal remnants. Their radiocarbon age is 29,000–28,000 years and this dating has been confirmed by TL analyses. The lower part is a well-developed forest steppe soil (MF_2).

The paleosol *Basaharc Double* (BD) comprises two forest steppe soils. Previously these were dated — from the rate of sedimentation in young loess — to 40-44 ka.

According to TL investigations by Y. LU and L. ZÖLLER, in the Paks profile *(Fig. 6)* the paleosol BD_1 is located between loess horizons of 114 ka and 144 ka old.

In the Mende-Basaharc series the *Basaharc Lower* (BA) paleosol is the oldest fossil forest steppe soil. The upper part of BA is mostly soil sediment, redeposited by solifluction over the slope. In the Cca horizon of the paleosol loess concretions in vertical orientation occur.

Based upon the earlier investigations and datings by M. PÉCSI it is assumed that the paleosol BA was formed in the lower part of last glacial period during a prolonged interstadial phase.

On the basis of recent TL dating in the environs of the Basaharc Double paleosol *(Fig. 6)* we can assume that BA paleosol may be the product of the R_1-R_2 interstadial and divides the two loess pockets (l_5 and l_6) of the penultimate glaciation.

The *Mende Base* soil complex (MB) consists of two paleosols. The upper member (MB_1) is 80-100 cm thick, chernozem-type soil, while the lower member (80 cm) is a well-developed brown forest soil (MB_2). The formation of this double soil had been placed into the last interglacial stage (PÉCSI, M. 1965, 1975; BORSY, Z. *et al.* 1979).

The paleosol MB is one of the best-developed soil complexes in Hungary, a marker horizon, which had been previously referred into the R_1-R_2 interstadial (BULLA, B. 1934; ŽEBERA, K. 1954). K. ŽEBERA regarded it of M-R interglacial age.

If we arrange the paleosols and loess horizons in a stratigraphic order or according to a chronological scheme (the MILANKOVITCH and BACSÁK climatic calendar or the isotopic stratigraphy), we certainly oversimplify reality; nevertheless, the paleosol *MB* can correlate with the *Mindel-Riss* interglacial period *(see Fig. 2)*.

Old loess series and paleosols

In the exposures of the bluffs along the Danube river the old loesses — almost 25 m thick — were named under the term *Paks series* (PÉCSI, M. 1975; PÉCSI, M. *et al.* 1977). Based upon their lithological properties they are subdivided into two parts by their lithological properties *(Figs. 1* and *5)*.

Upper part of old loess (Paks I series)

The upper part of the Paks series contains several erosional hiatuses *(Fig. 1)*. Based on lithostratigraphical, paleopedological and paleontological considerations, the fluvial sand and silt S_1, under old loess L_2, had been referred to the *Mindel-Riss* interglacial (ÁDÁM, L. - MAROSI, S. - SZILÁRD, J. 1954; KRIVÁN, P. 1955; PÉCSI, M. 1975; PÉCSI, M. & PEVZNER, M.A. 1974). It is probable that the fluvial sand S_2 was deposited in an earlier interglacial (G/M) and during its accumulation part of the old loess could have been eroded *(Fig. 1)*. Thus, the upper part of the Paks series may not represent the complete stratigraphic sequence of the Middle Pleistocene (but only that of the Mindel glaciation, *Fig. 2*).

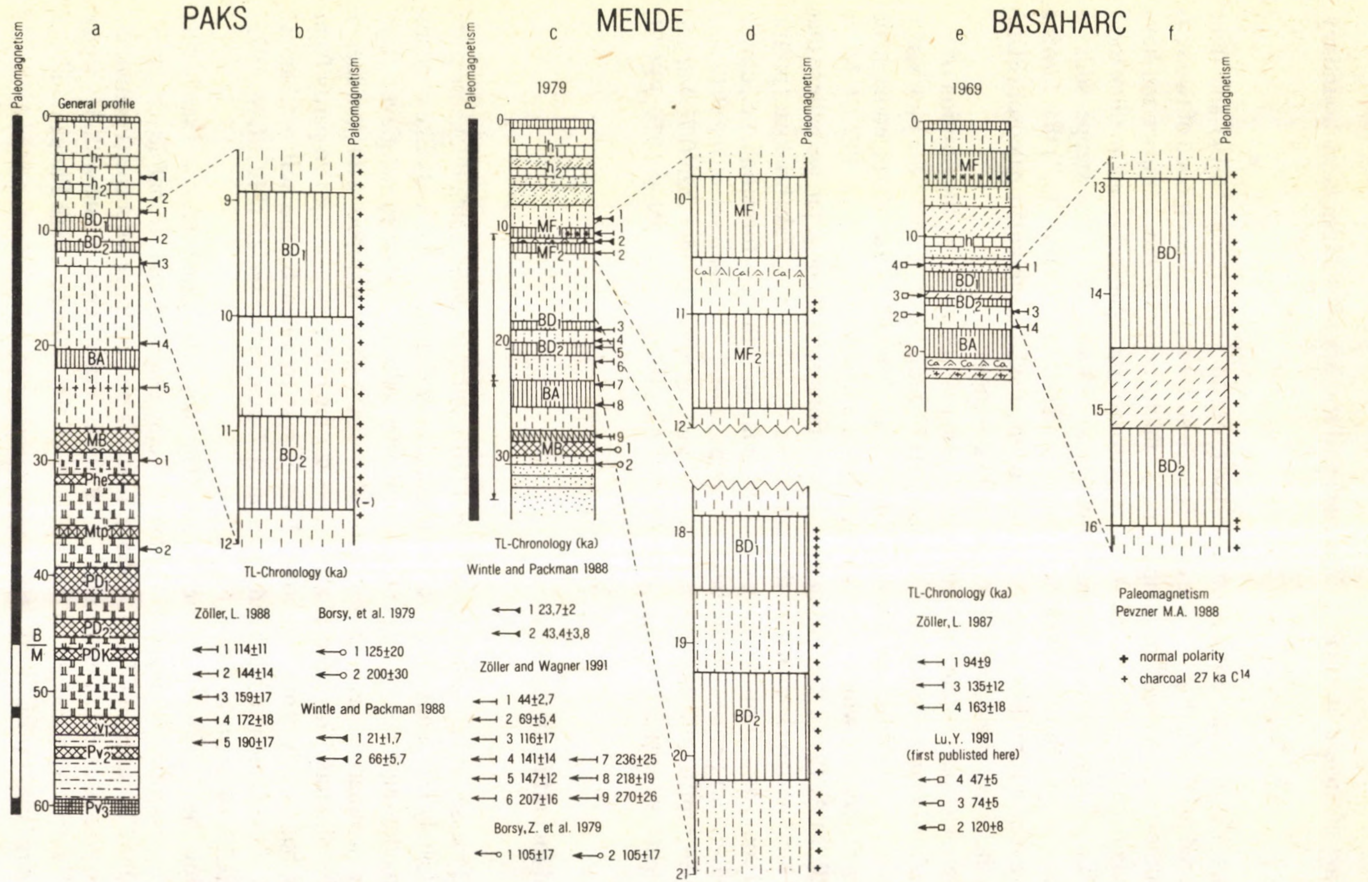


Fig. 6. **Chronological subdivision of loess profiles at Paks, Mende and Basaharc with paleomagnetic, TL and ^{14}C data (by PÉCSI, M. 1990). Different TL methods of dating resulted in extremely diverse ages. Segments of profiles b, d and f were been investigated three times and showed normal polarity each time (analyses were carried out by PEVZNER, M.A. and MÁRTON, P. in 1988–1990 and first published here).**

Lower part of the old loess (Paks II series) and the Brunhes-Matuyama boundary (0.7 Ma)

This 15 m thick series comprises three old loess horizons (L_4-L_6) and three brownish red paleosols *(Fig. 1)*. The *Paks Double* soil complex is comprised of two soils that are almost equally well-developed, 1.5 m thick, brownish red, compact and have medium clay content (PD_1 and PD_2). These paleosols are separated by a 2 m thick loess horizon (L_4). They may be the remnants of well-developed forest steppe soils of Mediterranean-type formed under dry conditions. The old loess (L_6', L_6") that forms a layer of several metre thickness at the base of the Paks-Dunakömlőd paleosol (PDK) represent the lower stratigraphic limit of the Paks series.

The *lower part of the Paks series* can be dated first of all by the position of the *Brunhes-Matuyama* paleomagnetic boundary (0.73 Ma). In addition, in the pink sandy sediment below the old loess series of Dunaföldvár probably the *Jaramillo* paleomagnetic interval is observable which is of 0.9 Ma absolute age (*Figs. 1 and 5*, PÉCSI, M. & PEVZNER, M.A. 1974). Relying on the investigations carried out so far, we believe that the oldest loess horizon known from the Carpathian Basin (L_6 in the Paks brickyard profile — *Fig. 1)* could have formed during the first glaciation with loess formation, i.e., during the *Donau glacial* period. On the basis of the paleomagnetic analyses of the Paks and Dunaföldvár profiles, the lowermost loess horizons seem to be older than 0.73 Ma and younger than 0.9 Ma (PÉCSI, M. & PEVZNER, M.A. 1974; MÁRTON, P. 1979; PÉCSI, M. 1984).

Subaerial formation below loess

Old loesses are underlain by subaerial formations of considerable thickness parts of which (sandy silt, sandy clay) were classed, also in Hungary, with loess-like deposits in their broader sense. Recently, the series of mostly red soils, red clays and gleyed clays — briefly summarized as 'variegated clay' series — was grouped with non-loessy terrestrial sediments. This series, located beneath the old loesses, is known partly from exposures but mainly from boreholes. First it was revealed by the soil mechanical boreholes of the Danubian bluff and was named *'Dunaföldvár series'* (PÉCSI, M. 1975, 1985a; PÉCSI, M. *et al.* 1979b — *Fig. 5)*.

Below the 50-60 m loess series ca. 30-40 m thick 'variegated clays' and sandy silts follow. The lowermost variegated clay and red clay layers of this 'Dunaföldvár series' belong to the Pliocene (PÉCSI, M. 1985a). In its base also Upper Miocene (Pannonian) sediment is found. In our opinion, the 'Dunaföldvár series' can correlate with the 'stony loess' of Central Asia and the Wucheng loess of the Chinese Loess Plateau and the underlying red clays (PÉCSI, M. 1987a).

An entirely different subaerial sequence is recorded in the *parts of the basin* which underwent *gradual subsidence during the Pliocene and the Pleistocene*. The thickness of basin deposits in the Hungarian Plain locally exceeds 500-1,500 m below the flood-plains of rivers. In the most intensively subsiding basins red soils and red clays are repeated 6-10 times between 600 and 1,000 m depths. With the preponderant flood-plain, meadow and chernozem soils, the swamp forests also allowed the formation of lignite. The boreholes did not reach the sequence of the Upper Miocene (Pannonian) inland sea to 1,200 m depth. The paleomagnetic study of the cores and paleontological data cover the whole of the Quaternary and extend to most of the Pliocene (5.25 million years B.P.; COOKE, H.B.S. *et al.* 1979; RÓNAI, A. 1977, 1985). In the Pliocene sequence 50-60 and in the Quaternary ca. 50 paleosol horizons are detected. Such a long Late Cainozoic geological record of subaerial sediment is only known to date from the exploration boreholes in the Hungarian Plain by A. RÓNAI (1985).

Long-term terrestrial records of the Middle Danubian Basin

In the Middle Danube Basin, loess and loess-like deposits cover various morpho-tectonic levels in ca. 150,000 km^2 total area. basin types of various elevation and size are predominant.

Under different geomorphological or morphotectonic conditions — *over an identical time interval* — the variation in the rate of basin subsidence produces various litho-and chronostratigraphical sequences.

The subaerial sequence of basins affected by prolonged subsidence in the Quaternary is subdivided by paleosols of larger number than the loess-paleosol sequence of basins, elevated plateaus or watersheds which underwent more moderate subsidence during the Quaternary.

1. *Young loess mantles* of small intermountain basins and mountain slopes (at 150-400 m above sea level). In the mantle of slope loess maximum 3 or 4 loess/paleosols and 2 or 3 slope debris layers overlie one another. Their age is < 25,000 years B.P.

2. *Low-lying terraces and alluvial fans*, flood-plain loess. The thickness of the loess series of the subsided alluvial fan is 40-50 m; it is of Pleistocene age and partly eroded. Flood-plain loesses are 2-5 m thick, occasionally subdivided by 1 or 2 paleosols. Their age is < 25,000 years B.P.

3. *Loess-paleosol-sand sequerces on pediments* (100-150 m above sea level). In the loess-paleosol-sand sequences of 50-100 m thickness ca. 12 loess, 10 sand and silt layers and 20-30 paleosols are present. The age of these profiles with hiatuses is Pliocene-Pleistocene.

4. *Loess-paleosol-sand sequences on alluvial fans and terraces* (10-100 m relative heights). The loess sequence is 40-60 m thick and subdivided by 10-12 loess horizons, 10-12 paleosols and 5 or 6 sand layers; LTR — Pliocene-Pleistocene.

5. *Subaerial basin sediment* locally of 500-1,500 m thickness. The surface of the basin is a flood-plain at 90-100 m above sea level. In the basin sediments the number of paleosols — mostly forest steppe and meadow steppe soils — may reach one hundred. In several boreholes there are 6-12 red soils or red clays between 600 m and 1,000 m.

12-16 intercalated sand layers are observed. The age of this almost complete sequence is 5.2-5.4 million years B.P. In the most intensively subsiding basins sedimentation was almost continuous; during Pliocene ca. 50-60 and in the Pleistocene ca. 50 soils developed (RÓNAI, A. 1985; PÉCSI, M. & SCHWEITZER, F. 1991).

In contrast on the non-subsiding foothills only 20-30 soils formed during the Pliocene and Pleistocene and several gaps are detected in the sequence.

Problems of worldwide correlation and dating of loess-paleosol sequences

1. A surprising global similarity was found between the lithostratigraphy of subaerial loess-paleosol sequences and the isotope stratigraphic records of deep-sea sediments. This similarity, however, does not mean that there is an absolute identity among these sequences. The only exact data in the chronological correlation of the twelwe most studied loess profiles on the Earth seems to be the B/M paleomagnetic boundary *(Table 1)*.

2. The interpretation of the location of the last interglacial paleosol is ambiguous, and various laboratories provided various TL dates. Last glacial loess is usually the thickest and best subdivided by various embryonic, arctic, tundra, steppe and forest steppe soils, recurring in 4 to 7 levels. The soil of the last interglacial in Central Europe is mostly a forest soil, has not yet been finally dated. Recent investigations indicate that a forest steppe soil formed under some drier, continental climate can also represent the last interglacial (column 8 in *Table* 2).

The number of marked paleosols, representing warm intervals varies from 6 to 9 above the B/M boundary. In addition 6 or 7 forest soils are assumed to occur. The identification of double soils or soil complexes still differs with profiles from which 6 to 10 loess horizons are described. Erosion gaps are not always shown *(Table 1)*.

4. *Typical loess* occurs down to the beginning of the Jaramillo event (ca. 1 Ma) in most of the loess profiles. Previously the formation of (red) paleosols with variegated clay and sand intercalations were characteristic (as at Krems-Stranzendorf, Paks-Dunaföldvár, in the Ukraine, Central Asia and on the Loess Plateau of China). On profiles reaching below the Matuyama/Gauss boundary (2.48 Ma) polygenetic red clays follow each other.

5. The paleogeographic conditions of the Jaramillo and previous periods did not favour loess formation. Soil formation (under submediterranean conditions) was predominant and cold spells were less marked. Instead of typical loess, loess loam, clay or sand developed.

6. Isotope stratigraphy suggests that 21 'glacials' and 21 'interglacials' occurred during the Brunhes and Matuyama epochs *(Table 1)*. Several loess profiles (nos 11, 18, 21, 22 and 23 in *Table 1*) attest that between the Jaramillo event and the M/G boundary

the number of paleosols exceeds that of the warm peaks on the isotopic curve. In addition, the existence of erosion gaps should also be considered, and this makes the layer-by-layer correlation of deep-sea and loess-paleosol sequences rather uncertain.

7. In the loess-paleosol sequences repeated intercalations of sand layers have been recorded. The series of superimposed paleosols, mostly in the older profiles allow conclusions for hiatuses or efficient sheet-wash. Consequently, in profiles with long-term record, in addition to the reconstruction of the various loess and paleosol layers, other processes (such as sand deposition, dell formation, cryogenic processes and sediment gaps) also have to be taken into account.

8. Although most of the researchers cannot identify paleosols in the Wucheng series, separating them from the intercalated (not always loessy) horizons and thus the number of paleosols is not known, the profile of the Chinese Loess Plateau seems to be one of the most complete subaerial records for the Upper Cainozoic.

9. The publications of recent years also suggest that the completeness of subaerial sequences and the number of buried paleosols is closely related to the geomorphological position of sediment series (uplifted closed basin, pediment or subsided basin under base level). Thus, for instance, in the Middle Danubian Basin, the sediment sequence of more than a thousand metre thickness contains almost 120 buried soils, including those dated to the Gilbert epoch. In the basins of the Chinese Loess Plateau of ca. 1,000 m altitude, however, the 150-330 m thick loess and other subaerial sequences contain 20-40 buried soils. When evaluating sedimentation gaps, the assessment of morphotectonic position is also indispensable.

10. In the past decade new principles and research techniques of great importance were introduced, particularly in loess chronostratigraphy and in the analysis of its physical and chemical properties. The magnetic susceptibility analysis of the loess-paleosol sequence seems to be one of the new methods of loess stratigraphy. Although still few, but a growing number of TL laboratories work and produce publications. There are, however, still significant differences between the results of the various laboratories and the TL method is only able to provide a minimum age for samples older than 100-150 ka.

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